Junior College Library

Volume XXXV May 1940 Number 3

Economic Geology

and the

Bulletin of the Society of Economic Geologists

TECHNOLOGY

CONTENTS

A Theory of Mineral Sequence in Hypogene Ore Deposits, Part I. ..... *Mark C. Bandy* 359

Rock Alteration in the Uchi Gold Area ..... *J. D. Bateman* 382

Phosphate Deposits of the United States ..... *George R. Mansfield* 405

Use of Sedimentation Features and Cleavage in the Recognition of Overturned Strata ..... *Philip J. Shenon and Roger H. McConnel* 430

Openings Due to Movement Along a Curved or Irregular Fault ..... *W. H. Newhouse* 445

Discussion and Communications:

The Geochemistry of Quicksilver Mineralization ..... *Joseph J. Fahey, Michael Fleischer and Clyde P. Ross* 465

Reviews:

Geology and Engineering (Legget) ..... *Edwin B. Eckel* 471

Finding and Producing Oil (Am. Petrol. Inst.) 473

Textbook of Geology, Part I, Physical Geology, 2nd Edit. (Longwell, Knopf and Flint) 473

The Throne of the Gods (Heim and Gansser, tr. by E. and C. Paul) 473

Textbook of Paleobotany (Darrah) 474

Books Received ..... *David Gallagher* 474

Scientific Notes and News 476

PUBLISHED SEMI-QUARTERLY

Five Dollars a Year, Seventy-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

Manuscripts for publication should be sent to the Editor, **ALAN M. BATEMAN**, at **Yale University, Yale Station, New Haven, Conn.** It is requested that contributors exercise care in writing *scientific* and *proper names*. References to other publications should be in accordance with the forms used in the pages of this journal. The manuscript should be typewritten with double space lines and must be preceded by *a brief abstract*. Galley proof will be sent authors only where a request to this effect accompanies the manuscript, or when, in the editor's opinion, the subject matter is such as will require correction by the author.

Reviews should conform to the journal usage. Review Committee: The Editor, C. H. Behre, L. C. Graton, J. T. Singewald, Jr., J. Gilluly, A. F. Buddington, W. H. Newhouse.

Books and Pamphlets for review should be sent to the Editor.

Reprints. Contributors desiring reprints of their papers may obtain them by filling out the order slip which will be attached to the galley proof when it is sent to the author. Provided the order slip is received by the editor, *with the return of the proof*, 50 reprints without covers will be furnished without charge. Reprints of discussions and informal communications are not furnished free of charge except when they exceed four pages in length when 50 will be supplied without charge. Reprints of reviews are not supplied. Additional reprints will be furnished at approximately the rates given in the table below when ordered *in advance of publication*. The rates apply only to plain text, with line engravings. Papers containing folded maps or plates will be more expensive.

The following rates *do not* include free carriage. *Postage or express must be paid by the author.*

	4 pp.	8 pp.	12 pp.	16 pp.	20 pp.	24 pp.	28 pp.	32 pp.	Covers
50 copies	$2.15	$3.35	$5.20	$5.40	$7.00	$8.00	$9.20	$9.85	$2.30
100 "	2.55	3.95	6.00	6.60	8.40	9.80	11.40	12.25	3.10
200 "	3.35	5.15	8.00	9.00	11.20	13.40	15.80	17.05	4.75
500 "	5.47	8.35	13.35	15.40	18.63	23.00	27.60	29.90	9.10

Standard covers are of the same style of type and paper as the cover of the journal, and bear the title of the article and name of its author. Special printing on cover is charged for at the cost of composition. Plates are $2.00 for the first 50 if printed on one side, and 1½ cents for additional ones; printed on both sides, $3.00 for the first 50, and 2¼ cents for additional ones.

Single copies of reprints (without covers) of many of the articles published in volumes issued since 1926 (Vol. XXI) are available at the following prices, upon application to the Business Editor, at Urbana, Illinois.

1-4 pp. 15c	5-8 pp. 20c	9-12 pp. 25c	13-20 pp. 30c	21-28 pp. 35c
29-36 pp. 40c	37-44 pp. 45c	45-52 pp. 50c	53-60 pp. 55c	61-68 pp. 60c

If illustrated by plates, add 3c for each plate if printed on one side, and 5c if printed on both sides.

Subscriptions. The price of the journal to subscribers in the United States and its dependencies is 75 cents for a single copy, or $5.00 a year for eight numbers. To subscribers in Canada, Cuba, Mexico, Spain, and countries in Central and South America, except Dutch and French Guiana, the annual rate is $5.30; to other countries, $5.75.

Forwarding. Subscribers wishing their journal to be forwarded to a new address should leave postage for that purpose with the Postmaster at their old address.

Missing numbers will be replaced without charge if claim is made within four weeks after the date of issue of the following number, provided that the neglect to receive them is not due to neglect to arrange for their forwarding.

Remittances should be made payable to the **ECONOMIC GEOLOGY PUBLISHING COMPANY**, and should be mailed to **W. S. BAYLEY**, Business Editor, Urbana, Illinois, to whom also all **Business Communications** should be addressed.

Foreign Agents. Thomas Murby & Co., 1 Fleet Lane, Ludgate Circus, London, E. C. 4, British Agents. The Maruzen-Kabushiki-Kaisha, P. O. Box 605, Tokyo Central, Tokyo, Japan, Agents for the Orient.

Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

es:
cember 15.
MAN, at
tors exer-
ould be in
d be type-
of will be
en, in the

tor, C. H.
house.

by filling
nor. Pro-
ts without
unications
50 will be
ts will be
ce of pub-
ing folded

aid by the

Covers
$2.30
3.10
4.75
9.10

urnal, and
ged for at
1½ cents
tional ones.
n volumes
ion to the

printed on

es and its
To sub-
America,
5.75.
w address
.
our weeks
eive them

UBLISH-
r, Urbana,

don, E. C.
al, Tokyo,

NCASTER, PA.

Junior College Library
Long Beach, California

ECONOMIC GEOLOGY

A SEMI-QUARTERLY JOURNAL

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: WILLIAM SHIRLEY BAYLEY
University of Illinois, Urbana, Illinois

ASSOCIATE EDITORS

CHARLES KENNETH LEITH
University of Wisconsin, Madison, Wis.

G. F. LOUGHLIN
U. S. Geological Survey, Washington, D. C.

C. N. FENNER
Geophysical Laboratory, Washington, D. C.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
Dallas, Texas

HEINRICH RIES
Cornell University, Ithaca, N. Y.

OSCAR E. MEINZER
U. S. Geological Survey, Washington, D.

PAUL RAMDOHR
Univ. of Berlin, Germany

L. C. GRATON
Harvard University, Cambridge, Mass.

E. C. ANDREWS
Sydney, Australia

PU

THE ECONOMIC GEO

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1940

G. F. LOUGHLIN.....*President*
W. D. JOHNSTON, JR.....*Secretary*
ALAN M. BATEMAN.....*Pres. Elect*
J. B. TYRRELL.....*Vice-President*
J. T. SINGEWALD, JR.....*Treasurer*
W. J. MEAD.....*Vice-Pres. Elect*

Councilors

1940	*1941*	*1942*
O. E. MEINZER	JAMES GILLULY	J. M. BOUTWELL
F. H. LAHEE	T. B. NOLAN	PAUL BILLINGSLEY
I. B. JORALEMON	PHILIP KRIEGER	L. C. SNIDER

Regional Vice-Presidents

M. K. SHALER.....Brussels, Belgium.....*For Europe*
J. A. DUNN.....Calcutta, India.....*For Asia*
J. A. BANCROFT.....Johannesburg, Africa.....*For Africa*
G. B. LANGFORD.....Toronto, Canada.....*For North America*
F. R. KOEBERLIN.....Santiago, Chile.....*For South America*
H. J. C. CONNOLLY.....Melbourne, Australia.....*For Australia*

Executive Committee

G. F. LOUGHLIN, *Chairman* — W. S. BURBANK
H. D. MISER — T. B. NOLAN — A. W. PINGER

Finance Committee

JAMES T. DUCE, *Chairman* — ARTHUR NOTMAN
S. H. BALL — W. J. MEAD

Program Committee

Q. D. SINGEWALD, *Chairman* — H. E. MCKINSTRY — D. G. THOMPSON

Committee on Publications

B. S. BUTLER, *Chairman* — E. L. DEGOLYER — W. C. MENDENHALL

ECONOMIC GEOLOGY

VOL. XXXV MAY, 1940 NO. 3

A THEORY OF MINERAL SEQUENCE IN HYPOGENE ORE DEPOSITS.

MARK C. BANDY.

ABSTRACT.

Progressive change in the ratio of the weight percentage of the anion radical to the cation radical as the fundamental control of sequence in deposition of minerals is the basic thesis of this paper. Evidence is given showing that oxide minerals are deposited in an "ideal" or "normal sequence" in such order that each mineral has a larger weight percentage in the anion radical than the next older mineral; sulphides are deposited after oxides with each younger sulphide having a smaller weight percentage in the anion radical than the next older mineral. Textures as a means of determining age relationships are discussed. Actual sequences of various classes of ore deposits are given and compared with the theoretical "normal sequence."

PART I.

CONTENTS.

	PAGE
Introduction	359
Historical Background	360
Textures or Patterns	363
Theories on the Cause of Mineral Succession	370
Ratio of Anions to Cations as the Control of Mineral Sequence	374
Factors Affecting the Anion-Cation Relationship in Minerals	378

INTRODUCTION.

THE writer proposes to show that in the average simple hypogene ore deposit ore minerals are deposited in a regular sequence, a sequence that can be predicted. The term "normal deposit" is used in this paper to describe a deposit that has had a simple history, generally a single period of fracturing and ensuing ore

deposition. Mineralization took place in a relatively stable environment. In this more or less ideal deposit the ore minerals were deposited in a "normal sequence," a term used in this paper to denote a sequence that the writer believes is the ideal toward which all deposition tends, a sequence indicated by a chemical balance between the anions and cations in the ore minerals. Evidence and data are advanced to show that the oxide minerals and the sulphides are deposited at separate stages. In each stage the base metals, *i.e.*, metals of the cation radical, have distinct periods of deposition. For example, iron is deposited in a "normal sequence" at one period and may be followed by other metals, but iron minerals do not precede and then also follow copper minerals.

The theory is advanced in this paper that progressive change in the weight percentage of the anion radical is a fundamental feature of a "normal sequence." In the oxide stage each succeeding (younger) mineral has a higher anion percentage than the preceding (older) mineral; in the sulphide stage each succeeding (younger) sulphide has a smaller anion percentage than the preceding (older) sulphide. This theory is based on the recapitulation and comparison of many ore suites studied in the field and laboratory over a period of years. Evolved as the theory that explains the greatest number of salient facts, it is herein advanced, not as a proven theory but as an aid to a better understanding of mineral sequence; a concrete theory that must be tested by other workers in this difficult field.

HISTORICAL BACKGROUND.

Before the microscope was applied in the field of mineralogy and geology little was written regarding the sequence of mineral formation in rocks and ores. A few references are to be found in older writings that describe the banding of ores in veins but even these references are vague regarding the actual paragenesis. The petrographic microscope encouraged consideration of the paragenesis of minerals in igneous rocks and after extended study Rosenbush first stated the rule that rock minerals crystallize from a magma approximately in the order of decreasing basicity with

decreasing age. In other words, during succeeding stages of crystallization, the magma has a constantly increasing silica content. This rule is accepted today, in a general way, by petrographers.

For several decades after the introduction of the petrographic microscope, extremely little progress was made in the technique of examination and determination of opaque minerals. Until 1906, when Campbell and Knight applied the technique of metallography to the examination of sulphide minerals, paragenesis of opaque minerals was a more or less undeveloped branch of geology. Prior to that time some work had been done on hand specimens and some successions are found scattered in the literature. Vugs were best adapted to the determination of paragenesis in this manner. In massive ores the criteria available were less definite and the successions determined were, in general, rather haphazard. Minerals with good crystal outline were regarded as late and rounded grains were regarded as older minerals that had been partly replaced and resorbed.

On the whole there is little to be seen megascopically in massive ores that sheds light on paragenesis and it was natural enough to come to the idea of simultaneous deposition. The term "simultaneous deposition" entered the literature and is still used to explain difficult or obscure sequence relationships. Ransome (29) after his study of the ores of the Globe District, Arizona (1903) makes the statement that

> As far as known, the minerals of the primary sulphide ores were contemporaneously formed and exhibit no regular sequence. Thus, in the Bobtail Mine chalcopyrite, sphalerite, galena, pyrite, and hubnerite occur together in a quartz gangue. None of the minerals named shows evidence of earlier or later origin than the others.

Since this statement was based on a megascopic study of the ores it was entirely justified.

With the application of the reflecting microscope, a new tool was offered, a more refined technique developed, and a great forward step was made in the determination of the exact paragnesis of ore minerals. Campbell and Knight (10) in the first microscopic examination of an ore suite using vertical illumina-

tion on polished surfaces, established the following mineral succession for the ores of the Temiskaming Mine:

Early	Smaltite
	Niccolite
(Fracturing)	
	Calcite
	Argentite
	Silver
	Bismuth
(Oxidation)	
Late	Erythrite and annabergite

This study marks the greatest step in the history of paragenetic studies of the opaque ore minerals.

As workers began to advance farther and farther into this field, a need appeared for a clear statement of the significance of the various common textures found in ores. In 1914, Graton and Murdoch (17) described a number of textures and interpreted their significance. This paper was followed by many others, but unfortunately the various writers were neither critical nor consistent in their use of terms, either in the use of new terms or in the interpretation of terms proposed by others. As a result, textural terms used by one writer with a definite significance would be used by another writer to describe other textures and might even be given other interpretations. Many textural terms lost their value and fell into disuse and other terms have been so abused that they are all but worthless today. Many standard textures common to certain minerals or groups of minerals in different mining districts were given diverse interpretations by different writers; this is still going on today and will no doubt continue for many years to come.

Many papers that discussed these textures and gave various interpretations are worthy of note (3, 22, 30, 33, 34, 43). A paper by Gruner (20) in 1929 is important in that it discussed the oriented intergrowth texture in a very complete manner. Several papers by Schwartz discussed the intergrowths of various copper minerals, especially the graphic type of intergrowth. In 1930, Lindgren (26) wrote an important paper discussing the eutectic and pseudoeutectic textures in ore minerals. This

work is a model of presentation and a definite interpretation is given to the textures described.

This period of textural description and interpretation probably culminated in 1931, in a paper by Bastin, Graton, Lindgren, Newhouse, Schwartz, and Short (5). A large number of textures are discussed in this paper and their significance in relation to the paragenesis and the origin of the minerals involved, is treated. This paper does not give a definite answer or interpretation to many perplexing problems but it tended to clarify the subject, although, to judge from papers written since then, its conclusions have not been generally accepted in many cases.

TEXTURES OR PATTERNS.

Texture or pattern is the primary and practically the only criterion now in use to determine the sequence of opaque minerals. A number of textures have been described and named, as mentioned before, and are used with more or less confidence by various workers. Some textures are more diagnostic than others but rarely do writers examine critically the textures they use. If a sequence is based solely on the study of polished sections of a suite of specimens, unaccompanied by detailed field work, the present writer would regard it as of little or no value. Yet the literature is filled with sequences based solely upon suites of specimens from mines the author has never seen. This is probably the cause of many of the contradictions existing in the literature today. It is not within the scope of this paper to discuss all the patterns that have been described and used, but a few of the more common ones will be discussed.

Vug Coatings.—This is probably the most satisfactory criterion available although it has a very limited application. There are several pitfalls in its use. In many deposits some minerals show a marked selectivity in coating other minerals. In these cases, unless the worker has a background of detailed field experience errors will be made. Specimens from Chojñacota, Bolivia, show crystals of chalcopyrite apparently overlapping crystals of sphalerite, yet detailed field work shows the principal stage of chalcopyrite to precede sphalerite.

Inclusions.—Inclusions are widely used to determine age relationships and many writers rely upon this texture without question. The writer regards this texture as unreliable and one that must be used with extreme caution. Fig. I illustrates a case that is believed to be misleading. The galena appears as inclusions and sphalerite shows a "caries" border against one of the inclusions, indicating that the sphalerite is "eating into" the galena, according to common interpretation. With oblique illumination, the galena is found to occur only at grain boundaries of the sphalerite, and the inclusions are more apparent than real. If the galena is replaced by sphalerite, certainly some

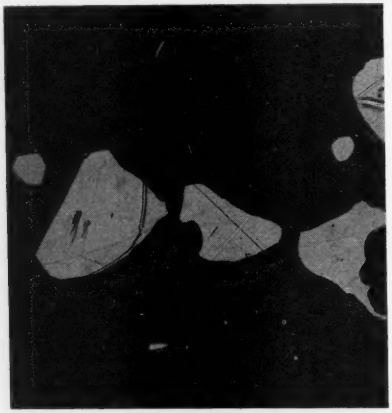


FIG. 1. Showing inclusions of galena (white) in sphalerite (dark gray) with minute exsolution (?) blebs of chalcopyrite in sphalerite. ×75. Quincy, Mass.

of it should appear within sphalerite grains. If both minerals were opaque, few workers would hesitate to place the sphalerite as the younger mineral. A decade ago inclusions, as an indicator of sequence, were seldom questioned by most writers, but as more and more critical work is being done they are becoming less important.

Caries Pattern.—This has been mentioned in the preceding paragraph. Where this pattern is developed to a considerable degree of perfection it can be used in many cases to indicate age relationships but as it is less perfectly developed it becomes useless or misleading. Only rarely can it be used with safety.

Network and Pseudomorphic Textures.—These are rarely developed and difficult to recognize. The network pattern formed by exsolution is similar to that formed by centrifugal replacement leaving an unreplaced rim. The latter texture is so rare and so difficult to establish that it is of little value and extremely misleading where incorrectly interpreted.

Veinlets.—Veinlets of one mineral crossing another mineral form a pattern that has long been regarded as infallable in mineral sequence determinations. Recently Graton[1] coined the term "antecedent veinlets" for veins with walls that have later been selectively replaced, so that the mineral now constituting the walls is younger than the vein. Such a relationship has been recognized by Graton in several ores. Hence, veinlets of one mineral crossing another may be either younger or older than the "host" mineral, and this veinlet pattern can only be used after critical examination. If used critically this is one of the best patterns in the writer's experience.

Grating Texture or Pattern.—The grating pattern and its variations is highly important in determining mineral sequence, and has direct bearing on the theory advanced in this paper. The term "grating pattern" conjures up a definite image in the reader's mind, *i.e.*, plates of the included mineral arranged along crystal planes of the host. However this term is unfortunately being extended to include patterns that have little in common with the above image. This pattern and its variations will be briefly considered.

Grating Pattern in Oxide Minerals.—The following grating patterns involving oxide minerals are mentioned in the literature,

Ilmenite in magnetite
Hematite in magnetite

[1] Personal communication.

Ilmenite in hematite
Spinel in magnetite
Rutile in magnetite
Rutile in hematite

These patterns have been interpreted as generally due to unmixing of a solid solution although it is generally recognized that a similar texture can be formed by replacement (5). Gruner (20) makes the point that "It is found that intergrowth takes place only on those crystallographic planes in which the atomic arrangement and spacing are almost alike," and gives atomic lattices to prove his point. It might be pointed out that many of the lattices are not similar but the periodicity in the two planes at the junction is the same. Even granting the validity of Gruner's generalization, these planes might also be the planes along which an atom could move with greatest ease, in other words, planes along which replacement could occur and leave the least external evidence.

Grating Pattern in Sulphide Minerals.—This pattern is less common in sulphides than in oxides. A number of grating textures have been reported that involve copper minerals and it is difficult to judge from the texts whether the textures are due to hypogene or supergene processes. The following textures, probably hypogene, are mentioned in the literature,—Chalcopyrite in bornite, dyscrasite in silver, chalcopyrite in stannite, cubanite in chalcopyrite, matildite in galena, brongniardite in cosalite, polybasite in galena. Inclusions of chalcopyrite in sphalerite (discussed below) rarely, if ever, form true grating textures as defined here.

In the oxides as well as in the sulphides, the included mineral in all cases has a higher anion percentage than the host mineral. In terms of the theory advanced in this paper, the included mineral in the case of oxides is a younger mineral than the host; in the case of sulphides, the included mineral is older than the host.

Inclusions of Hematite in Ilmenite.—Irregular, lens-shaped inclusions of hematite in ilmenite (27, 35) are mentioned in the literature and commonly regarded as due to exsolution. Definite

proof against replacement is lacking, however. In the writer's experience these inclusions never develop the true grating texture as shown by the other oxides mentioned above. The anion percentage relationship of these two minerals is opposite to that of the rest of the oxide minerals.

Oriented Bleb Inclusions.—Oriented inclusions of blebs, dots, dashes, and rods of minerals in sphalerite and stannite form a well known texture. The more common minerals showing this relationship are chalcopyrite in sphalerite, pyrrhotite in sphalerite, chalcopyrite in stannite, sphalerite in stannite. These inclusions may be well oriented or distributed at random in the host. They are generally considered to be the result of exsolution, although in some cases they are regarded as due to replacement. The writer is making a study of this texture in the field and laboratory and the results will be published at some future date. It should be pointed out that the included mineral contains a higher anion percentage than the host in each case. The host mineral is younger than the included mineral, judged by the "normal sequence." Can this texture be used as a criterion of sequence in that the included mineral represents an older mineral replaced by the younger (host) mineral with subsequent exsolution?

Mutual Texture. The mutual texture or pattern, first described by Graton and Murdoch (17) in 1914, was believed at that time to be diagnostic of simultaneous deposition of the minerals having mutual boundary relationships. Since it was first described the term has been frequently applied to cases in which true geometric mutuality is lacking. The "normal sequence" theory does not support the idea of true simultaneous deposition except as an unimportant process, taking place under exceptional conditions. The minute inclusions of minerals in galena, too small to determine, may be a case of simultaneous deposition. When a true mutual texture is encountered the "normal sequence" would indicate which mineral is the older. Fig. 2 shows such a texture. The "normal sequence" would indicate that the chalcopyrite is the older mineral, being replaced by bornite. Carrying the application of this theory one step further, should

supplementary data show the chalcopyrite to be definitely younger, careful search would be made for evidence of supergene deposition or hypogene deposition under unusual conditions.

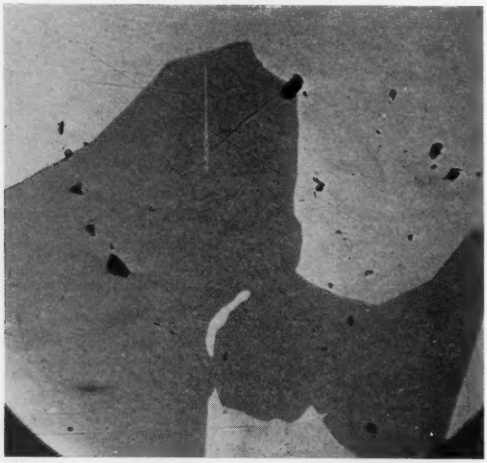


FIG. 2. A mutual texture of bornite (dark gray) and chalcopyrite (light gray). From this texture alone it would be difficult to determine age relationships of the two minerals. ×80. Bingham, Utah.

Eutectic, Pseudo-eutectic, and Graphic Textures. The difficulties inherent in the interpretation of the mutual texture are found in these textures. The term "eutectic texture" is gradually dropping out of the literature. If the term "eutectic" is used in its strict sense, few, if any ore textures would fall in this type as pointed out by Fenner (14).

Since the paper by Lindgren (26) on pseudo-eutectic textures, workers have become more critical of this texture. References to simultaneous deposition as the origin of these textures are rapidly disappearing. Much of the discussion regarding these textures revolves around the mineral allemontite. This mineral is an alloy of arsenic and antimony and outside the field of application of the "normal sequence" theory.

Dendritic Texture.—Some minerals form dendritic or skeleton crystals and then fill this framework. Later minerals may replace, preferentially, either the skeleton or the outer portions. This gives rise to very striking textures that, when recognized, can be interpreted with ease. Failure to recognize this texture has led to much confusion and error. For example, what is the significance and origin of the skeleton crystals of sphalerite (zincblendesternchen) in chalcopyrite at Ducktown, Tenn. (13); Ivigtut, Greenland; Hyder District, Alaska (22); Kaveltork, Sweden; and Pfunderer Berg, Tyrol? There is no agreement in the literature yet this is a widespread texture.

The writer has no wish to question the general value of texture in determining mineral succession. This must remain the ultimate criterion. However, there is at present a widely divergent and in many cases a more or less evenly divided opinion as to the significance and interpretation of many of the more important textures and little or no agreement on any of them. In the case of many deposits there is no agreement as to the mineral succession even where studies have been made by equally competent workers. Unfortunately, at the present time, library facilities are not available to the writer and definite comparisons of agreements and consistency between different workers on individual deposits cannot be made. The reliability of interpretation of textural relationships depends a great deal upon the experience of the worker and yet, with experience, one unconsciously develops certain prejudices in regard to individual sequence relationships and becomes less critical of the varying textural relationships these minerals may show. Beginners in the field of mineralography will naturally have a tendency to accept certain textures without question and sequences based on these textures will be recorded in the literature. Mineralography is a branch of the science of ore deposition in which there is a very small percentage of specialists in proportion to the number of actual practitioners and certainly there is no great amount of agreement among the specialists.

The theory herein advanced is not a panacea and cannot be

followed blindly. It may prove to be as valueless as some of the textures that have been used from time to time and then discarded. To the writer, the one advantage the theory possesses above all others is that it offers a concrete measure by which all sequences can be judged. It is admitted that many ore deposits, in fact the majority, do not agree entirely with the "normal sequence" but these are the deposits where the application of the theory should prove to be of the greatest value. The disagreements serve as warnings and should create a more critical attitude on the part of the worker. Disagreements should produce one of two results: first, a more critical study of the textures to check the sequence and if the textural interpretations were correct, one should study the depositional environment looking for causes of reversals, or more than one period of mineralization. The second result would be an absolute disagreement with the "normal sequence" theory and as these disagreements decreased or accumulated the theory would thereby be either strengthened or discarded.

THEORIES ON THE CAUSE OF MINERAL SUCCESSION.

Long before the introduction of mineralography as a branch of economic geology, experiments were conducted in the attempt to ascertain the cause and order of deposition of simple sulphides from ore-bearing solutions. As long ago as 1837, E. F. Anthon (1) studied the precipitation of metals from soluble salts by insoluble sulphides. A similar but much more elaborate series of experiments were carried on in the eighties of the last century by Schürmann (32). In each of these investigations a series was established, in which the sulphide of any one of the metals in the series would be formed at the expense of any sulphide lower in the series. The series of Schürmann is given on a later page. This series is somewhat analogous to the well known electrochemical series of the chemical elements. Schürmann considered the series to represent the order of the "affinities" of the metals for sulphur.

An important paper appeared in 1915 by R. C. Wells (50)

on the effect of solubility in precipitation of ore-forming compounds. The conclusions reached by Wells are of considerable importance regarding the precipitation of sulphides from aqueous solutions. He concludes that

> The concentration of the sulphur ion is so greatly affected by change of acidity that this change is the principal factor determining the precipitation of sulphides.
>
> The solubility of the several sulphides, however, differs so greatly that complete separations by fractional precipitation are possible, for example, copper from zinc.
>
> A mixture of two metallic salts yields by fractional precipitation an initial precipitate containing the sulphides of both metals, but as a rule, if the mixture is heated or is permitted to stand, one sulphide largely or wholly redissolves.

Earlier than the work of Wells, Weigel (49) had shown from his experiments the relative solubility, in water, of the common sulphides to be, Hg, Ag, Pb, Cu, Zn, Ni, Fe, Mn, reading from the least soluble to the most soluble.

A tabulation of the results of these three investigations is given below for comparison.

Schürmann (1888) and Wells (1916) Pd, Hg, Ag, Cu, Bi, Cd, Sb, Sn, Pb, Zn, Ni, Co, Fe", As, Th, Mn.
Weigel (1907) Hg, Ag, Pb, Cu, Zn, Ni, Fe, Mn.

The difficulty in applying these sequences to ore deposits is that the ore minerals as a rule come out, not as the common sulphides but as compounds of more than one metal. Consider the three metals, copper, lead, and iron. Lead falls between copper and iron in relative solubility, yet in ore deposits the bulk of the lead is deposited after both copper and iron. These series represent precipitations from aqueous solutions that differ from natural hypogene solutions. There are a number of disparities between the conditions of these experiments and natural conditions that stand in the way of any close application to natural phenomena.

Relation of Mineral Properties and Paragenesis.

The physical and chemical properties have been recognized to vary with the position of the different minerals in any general paragenetic sequence. An early paper by Gilbert (16) stressed

the relationship of hardness of minerals and mineral succession. In 1928, Newhouse (28) sought to summarize all the factors that appear to vary in a general mineral sequence. His tabulation is a very thorough one and as a result of the study he concluded that the dominant factor is solubility; and, based on the findings of Schürmann, Weigel, and Wells, he concluded that the early formed minerals are the more soluble and the later minerals are relatively insoluble, an erroneous conclusion according to the experience of the writer. Some of the factors mentioned by Newhouse and others, as well as some additional factors that the writer has never seen mentioned in the literature are discussed below.

Hardness and Power of Crystallization.—The conclusion reached by Gilbert (16) is that the older the mineral in a given sequence, the greater is its power of crystallization and the harder the mineral. This is true for many minerals but it would be difficult to use it as a critical check on a given sequence. Consider the relative powers of crystallization of chromite and stibnite, pyrrhotite and galena. It would be difficult to establish the sequence of pyrrhotite, pentlandite, chalcopyrite, sphalerite, stannite, and tetrahedrite on the basis of hardness. If one considers the general sequence to be oxides, sulphides, elements, then there is a certain agreement with the conclusions of Gilbert. Tertsch (41) has made a study of hardness of minerals and concludes that hardness is in part due to atomic structure, although minerals of the same structure vary widely in hardness. His tabulation of minerals according to contained elements shows some relationship between hardness and ionic radii.

Atomic Weight.—Atomic weight variations must be compared with elements and not compounds, except in a general way. Many elements occur in the form of both oxide and sulphide or sulphide and element but probably iron and very improbably tin are the only elements that occur in all three forms in hypogene ore deposits, or igneous rocks. With oxides preceding sulphides and sulphides preceding elements, it is impossible to establish elements according to atomic weight and compare them with a

general sequence except in a very broad way. In general, elements of low atomic weight are early and occur in deposits of close magmatic affiliations. Elements of low atomic weight have a greater tendency to form primary oxides, and those of high atomic weight have a greater tendency to occur as sulphides and natural elements.

Melting point.—Among the oxides there appears to be a progressive increase in the melting point with decrease in age.

		Melting point
Early	Cassiterite	1127° C.
	Magnetite	1538°
	Hematite	1560°
Late	Rutile	1640°

Later in the paper evidence is offered to establish the foregoing as a general succession. In the case of sulphides there is no such agreement between a general sequence and the melting points. A few melting points are given as an illustration.

	Melting point
Molybdenite	1185° C.
Pyrite	1171°
Galena	1114°
Niccolite	968°
Pyrrhotite	700°
Argentite	175°

Boiling Point, Vapor Pressure, and Molecular Volume.—Data on these properties are so few that relationships to a general sequence cannot be discussed to any advantage.

Heat of Formation.—There are few data available on the heats of formation of minerals. Available data on three oxides show a consistency with a general sequence, namely, an increase in the heat of formation with a decrease in age.

Early	Cassiterite	578 joules
	Magnetite	798 "
Late	Hematite	1117 "

It is to be observed that heats of formation vary in general with melting points.

Density.—Density is considered to increase with a decrease in age of formation. In the case of sulphides this is true as a broad

generalization, but there are many exceptions. In the case of oxide minerals it would appear that there is a decrease in density with decrease in age, an opposite trend from sulphides.

Other Properties.—There are a number of other properties that vary in a general way in a sequence but they are so vague and the exceptions so numerous that they have little value. An example is the complexity of chemical composition. Since later minerals commonly carry more elements, and impurities are more common and abundant in many cases, there is a general increase in complexity with decrease in age. Also, with more elements, the molecular structure becomes more complex.

Of all the properties mentioned in the foregoing paragraphs hardness is the most closely tied to sequence. It is related to the particular way in which atoms combine to form crystals and this in turn depends upon the physical-chemical conditions prevailing at the time of composition.

RATIO OF ANIONS TO CATIONS AS THE CONTROL OF MINERAL SEQUENCE.

As already stated in the introduction, progressive change in the ratio of the weight percentage of the anion radical to the cation radical as a fundamental of difference in age of deposition of minerals constitutes the basal thesis of this paper. The theory was developed by the writer over a period of years and was believed by him to be original. After access to library facilities, he has found that, like many other ideas, the germ of the idea can be found in earlier writings in one form of statement or another. Schürmann (32), in explaining the order of deposition of sulphides in the experiments he conducted, points out that the elements in the sequence he had established show a varying sulphur content.

> Diese Abweichungen hängen wohl ohne Zweifel damit zusamen, dass in den verschiedenen natürlichen Familien die Affinität zum Schwefel in sehr verschiedenen Weise . . . zunimmt.

In 1928, Newhouse (28) made the statement,

Parallel to this change in hardnes is a general increase in weight percentage of metal content down through the sequence with a complementary decrease in amount of sulphur.

Although the conclusions offered in this paper were arrived at independently of any work of others, no claim can be laid to priority.

Some years ago the writer started to study the causes of mineral deposition in an orderly sequence as exemplified in a number of hypothermal and mesothermal deposits. Over a period of years he had had an opportunity for field study of a number of deposits, most of them simple hypothermal and mesothermal. A number of sequences were selected and minerals in each sequence, whose position had been established beyond reasonable doubt both in the field and laboratory, were combined into a general sequence and this general sequence and the individual sequences were examined. It was felt that there must be some order to mineral deposition in ore deposits; that it was not haphazard; that it should be predictable. At the beginning it was apparent that the oxides preceded the sulphides and the sulphides were followed by the native elements.

The physical properties of the sulphides were examined but, aside from hardness, no other property was generally consistent. Hardness was too indefinite to be used as a check and was useless in predicting a relationship between two minerals. When the chemical composition was tabulated it was immediately apparent that there is a definite relationship between the weight percentage of the anion radical and the age of the mineral. From this beginning a critical study was made of such ore suites and mines as opportunity permitted. During the study many ideas were discarded and the original concept of the theory was modified to a considerable extent.

Stating the theory in its general form the writer holds that the sulphide minerals are deposited in a "normal" or "ideal sequence" in such a manner that each succeeding sulphide contains a smaller weight percentage of the anion element or elements and a greater weight percentage of the cation element or elements than

did its immediate predecessor. The oxides follow an opposite trend, the weight percentage of the anion element is greater in each succeeding (younger) mineral.

Definition of Terms.—By "normal sequence" the writer has in mind the sequence of deposition that would presumably take place in any ore deposited under "normal" or simple and ideal conditions, *i.e.*, not subjected to crowding, telescoping, stretching, etc., during deposition, or rejuvenation of mineralizing solutions, effective changes of wall rock along the vein, or similar changes common in ore deposits.

Anion is used in the sense of the sum total of those elements that act as negative elements in mineral combinations. In arsenopyrite, FeAsS, the sulphur and arsenic together make up the anion of the mineral and iron the cation. In enargite, Cu_3AsS_4, sulphur alone makes up the anion and copper and arsenic the cation.

A General Survey of the Problem.—To illustrate some of the problems of mineral succession, the following sequence may be examined.

	Cation.							Anion.		
	Fe%.	Ti%.	Ni%.	Cu%.	Sb%.	Pb%.	Au%.	O%.	As%.	S%.
OXIDES (Early)										
Magnetite	72.4							27.6		
Hematite	70.0							30.0		
Ilmenite	36.8	31.6						31.6		
SULPHIDES										
Arsenopyrite	34.3								46.0	19.7
Pyrite	46.6									53.4
Pyrrhotite	60.4									39.6
Pentlandite	42.2		22.0							36.0
Chalcopyrite	30.5			34.5						35.0
Bornite	11.1			63.3						25.6
Tetrahedrite				52.1	24.8					23.1
Bournonite				13.1	24.7	42.5				19.7
Galena						86.6				13.4
ELEMENTS (Late)										
Gold							100.0			

Portions of this "normal sequence" are described from many deposits. In the oxide sequence the decrease in the cation con-

tent and an increase in the anion, oxygen, content is to be noted. Rosenbusch stated that minerals crystallizing from a magma caused a constant concentration of the acid elements of the magma in each succeeding period and the minerals themselves were more acid in each succeeding period. Oxides, that are so closely related to the magma in time, space, and mode of formation, apparently follow this same rule in most ore deposits or hypogene concentrations of oxides.

The sulphides represent another type of deposition. In all "normal deposits" the writer believes that there is a chemical "break" between the period of oxide deposition and the sulphide period, and once this line between the two types of minerals is passed, oxides will not form again.

In the foregoing sequence it is to be noted that the cation percentage of iron rises from a low figure to a maximum and then drops off again, the maximum percentage occurring in the mineral pyrrhotite. Following pyrrhotite, the percentage of iron decreases and copper appears likewise rising to a maximum in bornite and decreasing in succeeding minerals. Following copper, lead reaches a maximum in the mineral galena. If nickel minerals had been included in the sequence it would have been found that the maximum for nickel follows the iron maximum. In this sequence as one metal rises to a maximum and then decreases and while the succeeding metal follows the same cycle, the anion percentage progressively decreases.

This concept of maximum percentages of various metals in a mineral succession has interesting applications to sequence studies. For example, after a period of pyrrhotite deposition, either entirely new minerals must form, *i.e.*, minerals with new cation elements, or, if iron is still present in the solution it must combine with some other element that is capable of forming minerals of higher cation content than pyrrhotite It would appear that once iron minerals start to form they continue to form until the iron is completely removed from the metallizing solutions. Interruptions do not occur in the "normal sequence."

An exception to the above statement might be cited. Bornite,

chalcopyrite, and enargite are commonly associated in ore deposits. If deposits that contain these three minerals result from a continuous, uninterrupted flow of solutions, depositing minerals under "normal" or "ideal" conditions, then the association of these three minerals stands as a contradiction of the "normal sequence" theory. This relationship is discussed later under the paragenesis of mesothermal deposits.

FACTORS AFFECTING THE ANION-CATION RELATIONSHIP IN MINERAL SEQUENCE.

The writer cannot express a definite conclusion regarding the cause or causes back of the cation-anion relationship in mineral successions. It is undoubtedly some physico-chemical control that affects the solubility and saturation or supersaturation of the minerals. As stated before, the writer believes that the solutions depositing oxides undergo some change of physico-chemical balance when they cease depositing oxides and begin to deposit sulphides. It is not certain whether available oxygen is an inherent quality in metallizing solutions in magmatic environments, *i.e.*, as regards deep seated deposits with high temperatures and pressures, or whether oxygen is abundantly supplied through dissociation of H_2O in the solutions due to sudden decreases in pressure with relatively no attendant drop in temperature. The writer is inclined to the latter view and believes that the oxides may "normally" be deposited from acid solutions, while the sulphides are "normally" deposited from alkaline solutions.

In other words, at high temperatures and pressures, temperatures and pressures above those of sulphide deposition, the ore solutions are "oxidizing." Reactions take place that provide abundant oxygen for the formation of oxide minerals. As cooling proceeds each succeeding mineral contains a higher percentage of oxygen. At certain temperatures and pressures oxides cease to form and the solutions pass into a physico-chemical environment in which only sulphides can be deposited. As this sulphide field is approached there is an oxygen ion pressure in the solutions that results in the formation of minerals that are oxygen-rich, so

to speak. Magnetite may be followed by hematite which extracts or uses up all the available oxygen and then, in the sulphide field, the iron deposition continues as pyrite.

After the metallizing solutions enter the sulphide field conditions change. At the higher temperatures the anion elements, principally sulphur, are available in quantity and it appears that conditions favor the deposition of anion-rich minerals. As more and more of the anion elements are extracted there is a constantly decreasing quantity available and the cation elements gradually extract, through combination, smaller and smaller amounts. If all the anion elements are combined and there is an abundance of cations, these will deposit as native elements or metals.

The foregoing analysis is entirely theoretical and the writer cannot support it at the present time with experimental data, nor can he quote the data of others. Should the theory of a "normal sequence" be favorably received, other workers, more capable than the writer, may be able to furnish data that could explain the cation-anion relationships in mineral sequences.

Reversals.—Before comparing various actual mineral successions with the theoretical "normal sequence," causes of reversals will be briefly considered. By "reversals" the writer refers to the deposition of high-temperature minerals after low-temperature minerals; an extreme example would be pyrrhotite following galena.

Any reversals that might take place in depth, in the near-batholith zone, due to suddenly reduced pressure or temperature as the ore solutions leave the igneous source, would tend to be obliterated. As pressure and temperature built up following any drop and with long continued flow of solutions, unstable minerals would be removed and deposited at their proper level. If drops in temperature or pressure occurred at higher levels the ability and opportunity for removing any unstable minerals would diminish as the surface was approached. Consequently, in the epithermal zone little agreement would be expected between the actual sequence of deposition and the theoretical "normal sequence." In other words, the deeper the deposit the closer should

be the agreement between the actual and the "normal" sequences, other factors being equal.

Llallagua, Bolivia, offers an illustration of a reversal with no subsequent readjustment. This is a typical high-temperature, low-pressure deposit, formed near the surface. As the first solutions reached this shallow zone there was a dumping of bismuthinite followed by a relatively long period of cassiterite and wolframite deposition. These oxides were rapidly deposited and there was no opportunity to remove this unstable mineral. Any bismuthinite however, that escaped coating by these oxides was removed later, with the result that uncoated bismuthinite crystals are very rare except late, acicular crystals deposited during the sulphide stage.

Wall rock undoubtedly exerts an influence on mineral deposition in many deposits and may or may not cause reversals. Reversals due to wall rock influence are very rare in deep-seated deposits and are uncommon even in shallow zones.

The writer believes, from field studies, that sudden drops in pressure with more or less constant temperature change mineralizing solutions from alkaline to acid. Sulphides are deposited from acid solutions in the reverse order from that of the "normal sequence." This change to acidity of the solutions is probably the most important single cause of reversals in shallow and intermediate deposits.

A deep-seated deposit consisting of a single strong vein is the ideal condition for close agreement between the actual and "normal" sequences. As the deposit becomes more complex structurally, it is obvious that the actual sequence will depart further and further from the "normal" sequence. In the case of large deposits with numerous veins, the literature indicates little agreement between actual and "normal" sequences. Likewise there is little agreement between the sequences determined by different workers, for example, Butte, Montana. In these large, complex deposits different periods of mineralization follow one another, usually accompanied by fracturing, and any attempt to determine a detailed mineral sequence that will apply to all

parts of the deposit is impossible. In different parts of the deposit a later, higher temperature period will be superimposed on a lower temperature, earlier period with reversals. Use of the "normal sequence" theory as a measuring stick leads to a better understanding of the conditions of deposition and aids in working out a complex history.

Other causes of reversals, such as heating of wall rocks, will not be considered. Reversals are common in mineral deposits but the writer believes that the "normal sequence" theory has an important application in this field. Reversals are caused by some unusual condition, some change in the orderly sequence of mineralization, and the "normal sequence" will give a clue to the condition, a clue to be followed up in the field or laboratory. In the light of the "normal sequence" such changes must be explained and may be found to be important or of no consequence. To the experienced worker certain unusual sequence relationships or reversals are highly suggestive.

(*To be concluded in the following number.*)

ROCK ALTERATION IN THE UCHI GOLD AREA.[1]

J. D. BATEMAN.

ABSTRACT.

A genetic relationship between granitic intrusion and gold deposition is proposed for the Uchi gold area, where it is shown that the intrusion of the younger granite, introduction of dike rocks, mineralization, and wall rock alteration are all related parts of a sequence of geologic events connected with a single period of magmatic activity.

INTRODUCTION.

For many years lode gold deposits in almost all parts of the world have been considered to have originated in the emanations derived from granitic intrusives. This belief, which has become so firmly rooted as to be axiomatic, is based on the widespread recognition of the spacial relations of granitic intrusives to gold deposits. Detailed geologic studies in many gold-producing districts show that the time of gold deposition post-dates the emplacement of the intrusive rocks, generally by a considerable geological interval; however, a genetic relation between gold deposits and intrusives is commonly accepted on the basis of suggestive field evidence, but can seldom be proven. This condition was recognized by E. L. Bruce (1),[2] who in 1937, pointed out that in the case of some gold fields in Ontario and northwestern Quebec, the relationship of the orebodies to the granitic masses is structural only; that is, that the massive intrusives acted as buffers to stresses, with the consequent localization of fractures in the rocks about them. Such fractures then formed favorable zones of permeability for later gold deposition.

More recently Henderson and Jolliffe have shown (2) that, at Yellowknife and Gordon Lake in the Northwest Territories, the gold deposits in the sediments are structurally related to early pre-

[1] Published by permission of the Provincial Geologist, Ontario Department of Mines.

[2] Numbers in parantheses refer to Bibliography at end of paper.

Cambrian folding, the quartz having been introduced along zones of weakness that resulted from Archean orogeny; whereas the gold deposits in the adjacent volcanics are related to late pre-Cambrian faulting. Bruce (3) has indicated that the gold deposits in the Lake Nipigon-Long Lake belt of northwestern Ontario are structurally localized by post-folding movements in the sediments and volcanics, and that the time of gold deposition is later than the intrusion of all the igneous rocks, excepting the late pre-Cambrian diabase.

The writer is entirely in agreement with the conclusions expressed by these workers, and has also observed many instances in which the relationship of gold deposits to nearby intrusives is obviously a structural one. But granting this, the genesis of the gold is still to be considered, and it is of interest, therefore, to record evidence from the Uchi Lake area that strongly suggests the gold deposits in that district originated in the late stages of the magmatic activity accompanying granitic intrusion.

Location.—The Uchi Lake area is situated in the district of Kenora (Patricia portion) in northwestern Ontario, approximately 75 miles north-northwest of Hudson or Sioux Lookout on the Canadian National railway, from which points it may easily be reached by airplane.

Mining Development.—Gold was first discovered in the district in 1926 as a result of prospectors spreading out from Red Lake, which lies some 50 miles to the west of Uchi Lake, following the Red Lake gold rush of 1925. Earlier development of gold prospects did not prove successful and interest in the district lapsed until renewed activity resulted in the development of a substantial tonnage of ore in the Uchi gold mine in 1937. This mine is now in production on a daily milling basis of 500 tons of ore, and a number of other prospects in the vicinity are currently undergoing a vigorous development.

GENERAL GEOLOGY.

The geology of the Uchi Lake area has been described by J. E. Thomson (4), whose report contains a detailed colored geologic map of the gold-bearing zone. In 1938, the writer made an ex-

amination of 170 square miles of the district and examined the gold occurrences in detail. As a result of this work, the following table of geologic formations is established for the area.

TABLE OF GEOLOGIC FORMATIONS.

PRE-CAMBRIAN (Archean)

Younger Intrusives

Altered basic dikes
Gold-bearing quartz veins
Quartz-feldspar and diorite porphyry
Pegmatite
Granite, quartz monzonite, granodiorite
(Amphibolite)

Intrusive contact—intense folding

Older Intrusives

Basic intrusives—metagabbro
Confederation granite porphyry and mylonitized equivalents.

Intrusive contact

Uchi series

Volcanic assemblage of greenstone, hornblende schist, amphibolite, carbonate schist, pillow and amygdaloidal lavas, porphyritic andesite tuff and breccia, rhyolitic tuff and breccia, and minor intercalated sediments.

Unconformity—gentle folding

Slate Lake series

Metasedimentary assemblage of mica schists, paragneisses, impure quartzite, arkose, sericite schist, iron formation, conglomerate, and intercalated greenstone flow rocks.

Summary of Geology.—The geological relationships of the rock formations are shown on Fig. 1. The Slate Lake metasedimentary series underlies the southeastern half of the map-area, and the Uchi volcanics the northwestern half. An older granite, known as the Confederation granite porphyry extends northerly through Bowerman and Mitchell townships. A number of long, narrow belts of metagabbro consisting essentially of saussuritic amphibolite occur as vertical sill-like bodies between the flows. These older intrusives have been involved in the folding of the volcanic and sedimentary rocks comprising the basement complex.

The Slate Lake metasediments and Uchi volcanics have been folded into vertical attitudes comprising an essentially homoclinal section within the map-area, the tops of the beds and flows facing the north or northwest, depending on their trend. Following the folding, there was injected a number of granitic bodies, principally

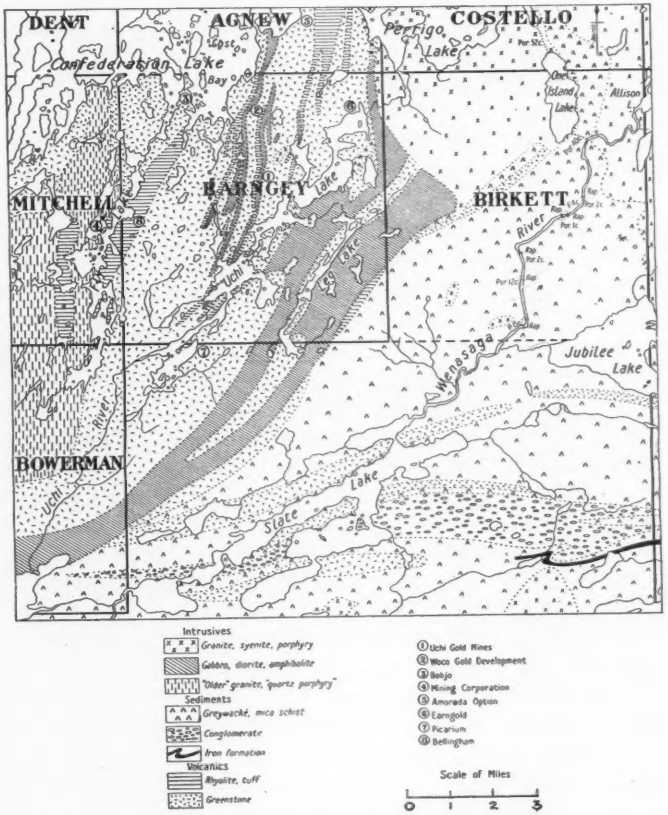


FIG. 1. Sketch map showing geological relationships of the rock formations in the Uchi Lake district. Locations of gold occurrences are shown by number.

represented in the area by the intrusive at Perrigo Lake consisting of a body some three miles in diameter, and the granite at Allison Lake, which is part of the western border of an extensive batholith. The Perrigo Lake granitic mass is intrusive along the contact of the Uchi volcanics and Slate Lake metasediments and, petrographically, the rock ranges in composition from a granodiorite on the western side of the intrusive to a quartz monzonite on the eastern side at One Island Lake. This change in composition is the direct result of contamination by inclusions in the magma, which were derived, on the one hand, from the basic igneous rocks of the Uchi series on the western side, and on the other, from the arenaceous Slate Lake sediments on the eastern side.

The granite at Allison Lake has a broad outer border zone of pegmatite that is up to one-quarter of a mile and more in width. This zone passes inwards to another broad zone in which the otherwise normal granite of the batholith has been altered to a muscovitized albitized granite containing small amounts of garnet and topaz. Numerous other small stocks and dikes of granite, diorite, quartz-feldspar porphyry, pegmatite, and other silicic and basic rocks occur throughout the area, but are most abundant near the loci of the major intrusives in Birkett township, and progressively decrease in numbers to the west and southwest. The spacial relationship of these dikes and stocks to the larger intrusives suggests a common origin, and the distribution of these sattelites further suggests that the district is underlain by granite which, at depth, slopes off to the southwest.

This concept has the additional support of a broad metamorphic zoning produced by the major intrusives on the older rocks. The gold deposits, most of which lie in a belt in the Uchi volcanics extending from the east side of Lost Bay southward along the west side of Uchi Lake, are related to this zoning. The gold-bearing quartz veins are later than all the dike rocks, excepting one group of post-vein basic dikes.

METAMORPHISM.

Prior to the intrusion of the granites and related rocks, the formations of the Uchi and Slate Lake series together with the older intrusives had undergone a deformational metamorphism as a result of regional folding. The metamorphism due to deformation is expressed in the district chiefly by the production of schistose rocks, and is also recognized by cataclastic mineral granulation along zones of shearing, but gold deposition is not predisposed to favor these zones and they do not show any tendency to be replaced by quartz.

Some of the thicker flow rocks and basic sills are not schistose, excepting near their contacts, and the primary igneous textures are unaltered. These rocks, however, have undergone a mineral reconstitution in the same direction as the schists, but which has not proceeded so far. That is, primary pyroxenes have gone over to amphiboles, whereas the amphiboles show only incipient alteration to chlorite. In the thinner and weaker flows, the pyroxenes and amphiboles have been replaced by chlorite. Cornelius (5) offers an explanation for this feature in the proposition that transformation of minerals may be independent of the formation of parallel texture and, consequently, that factors determining tectonic schistosity are not necessarily determining factors in mineral transformation. He would thus explain this condition of neomineralization in massive rocks as going in the same direction, although not as far as in the schists provided that regional temperature and pressure conditions remained the same and, since they might be expected to do so for some time, mineral reconstitution would persist after the cessation of deformation.

The pre-folding basic sills were, for the most part, originally gabbros but now consist essentially of blue-green metamorphic amphiboles and saussurite. As these rocks must have been raised to a relatively high temperature condition during the intrusion of the later granites, their present alteration is to be regarded in this light rather than as a result of tectonic deformation only. The amphiboles are somewhat similar to secondary blue-green actinolitic amphiboles that have been described from New Zealand by C. O.

Hutton (6), and which are reported to contain a high proportion of ferric to ferrous iron and an appreciable content of soda, both of which are probably responsible for the color. The amphiboles from the Uchi Lake district are true hornblendes rather than actinolites and different grains show a variation of the axial angle, even in the same thin section, which suggests a solid solution series that varies from grain to grain. These amphiboles are undoubtedly of secondary origin and it is probable that the blue color is the result of the addition of some glaucophane and riebeckite molecule. Eleven determinations of the specific gravity of the saussurite amphibolites range from 3.02 to 3.10, the high density being partly accounted for by the alteration of original feldspars to compact minerals of the epidote group. The accompanying photomicrograph (Fig. 2) is representative of the texture of these rocks in thin section. In many thin sections the ghosts of feldspar crystals, now entirely replaced by saussurite, may be observed; and in areas where hydrothermal action is known to have been present, as in the neighborhood of the gold deposits, the proportion of epidote increases at the expense of the hornblendes. Post-folding dikes of similar composition that are not known to have undergone any tectonic activity have suffered identical mineral alteration and thus is it concluded that the alteration of the metagabbro sills is principally the result of the action of later granitic intrusion.

That the granitic intrusives were capable of such action is seen in the intrusives themselves, in the contact metamorphism produced in the rocks themselves, as well as about their borders.

The Perrigo Lake granitic mass contains abundant small inclusions of the invaded rocks, which may be observed in all stages of digestion by the intrusive. The inclusions on the eastern side, derived from the impure quartzites of the Slate Lake series, consist essentially of mica schists that are similar to the contact zone of mica schists in the sediments bordering the intrusive body. Commonly in the contact zone the textures are crystalloblastic and the rock is essentially a granulite as shown in Fig. 3. Biotite is the chief dark mineral of the inclusions, contact sediments, and of

the quartz monzonite itself in the eastern part of the body. To the west, however, where the basic volcanics and metagabbro have been invaded, hornblende is the chief dark constituent of the intrusive and the inclusions, and is present with biotite in a ratio of more than 3 : 1. The inclusions consist of fresh-appearing amphibolites as shown in Fig. 4, the texture being crystalloblastic and the light minerals consisting essentially of calcic oligoclase. The contacts of the inclusions as observed in thin sections are commonly rimmed with biotite against the granodiorite. The principal feldspar of the granodiorite, oligoclase, is present in a ratio of 2 : 1 with microcline and microperthite but, in a narrow border zone about the inclusions, the granodiorite is free of potash feldspars, whereas the plagioclase is zoned. This impoverishment in potash in a zone about the border of the inclusions is the result of K_2O being taken up in the peripheral concentration of biotite, suggesting a movement of salic constituents towards the inclusions. On the other hand, hornblende may occur in the granodiorite surrounding the inclusions and, in some instances, is concentrated in a narrow zone encircling the inclusion (Fig. 6). This suggests a movement of mafic constituents outward from the inclusion into the intrusive. That is, there has been an exchange of material resulting in the contamination of the intrusive magma and thus producing the present rock type. The product of contamination in this case is dependent on the chemical compositions of the intruded rocks, and the petrographic variation from granodiorite to quartz monzonite across the intrusive is a direct response to the chemical compositions of the invaded rocks. There is no evidence of melting of the inclusions, the exchange taking place by chemical reaction. Without this contamination the final product would probably have been close to a normal granite.

Similarly, the Perrigo Lake intrusive has produced a profound contact metamorphic zone in the basic rocks to the west, in which the greenstone schists and basic intrusives that generally have a pathologic appearance have been altered to fresh appearing amphibolites (Fig. 5), which consist essentially of fresh hornblende and idiomorphic porphyroblasts of zoned oligoclase.

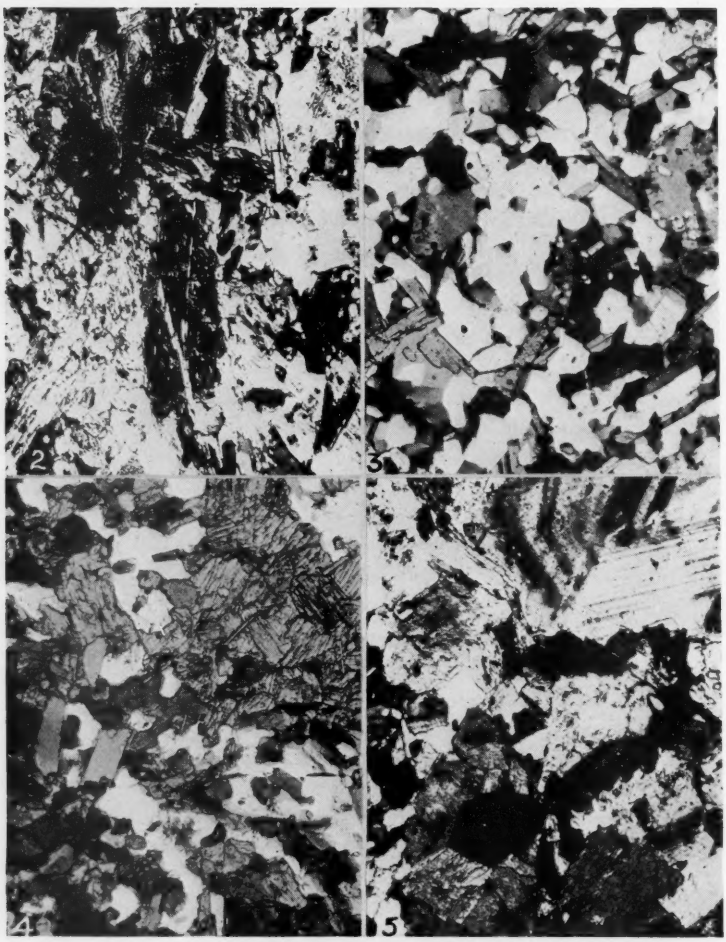


FIG. 2. Thin section of metagabbro. x nicols; × 40. Metamorphic texture of amphiboles (dark with cleavage) set in a mat of saussurite (light).

FIG. 3. Contact metasedimentary granulite from Slate Lake series on east side of Perrigo Lake intrusive. x nicols; × 160. Light areas con-

The alteration of the granite comprising the border of the batholith at Allison Lake has been mentioned. This consists of the widespread development of pegmatite and the albitization and muscovitization of the granite itself. Much of the muscovite has replaced biotite, and the alteration has resulted in a net gain in soda and a net loss of iron. Small amounts of garnet and topaz have also been formed. This type of alteration, which is as much as a mile wide along the western border of the batholith is thought to be deuteric in origin. The sediments for a distance of two or more miles outward from the batholith are relatively high-rank metamorphic rocks consisting mostly of paragneisses and schists showing local development of staurolite and garnet. They are intruded by numerous pegmatites that are identical with the pegmatite of the border zone within the batholith.

These rather lengthy comments are given to show the potent chemical activity of these intrusives. The batholith is part of the regional granite surrounding the Uchi Lake schist belt, whereas the Perrigo Lake granodiorite is a stock or small batholith within the schist belt itself, but spacially related to the larger outlying batholith. There is no evidence to suppose that these two intrusives are different in age and they are thought to have been derived from the same magma and intruded at the same time, their differences being due to the environment during intrusion and to the effects of deuteric alteration. The granodiorite thus represents a stock above the main batholith which, here, underlies the schist belt. A number of other small stocks of silicic intrusives, most of which are too small to be shown on the sketch map, occur in the eastern part of the area, suggesting that the main body of the surrounding granite lies at no great depth.

---

sist of quartz, oligoclase and microcline; grey areas are biotite laths. Note crystalloblastic texture.

FIG. 4. Crystalloblastic amphibolite from a greenstone inclusion in the Perrigo Lake granodiorite. × 160. Hornblende (showing cleavage) and biotite are grey; white areas are calcic oligoclase.

FIG. 5. Amphibolite (metagabbro). Photomicrograph of specimen from west side of Perrigo Lake intrusive. x nicols; × 40. Oligoclase (light) and hornblende (dark) occur in a granoblastic texture.

METAMORPHIC ZONING.

The volcanic rocks of the Uchi series, and the basic intrusives, contain minerals that are more susceptible to alteration than the minerals in the Slate Lake sediments. These rocks are, therefore, a more delicate indicator of metamorphism. The predominant mineral throughout the basic rocks of the district is hornblende, and most of the basic flows and intrusives are hornblende schists and amphibolites. There is a notable lack of chlorite in the rocks of the area, excepting in the western and southwestern portions. Most of the greenstones of early pre-Cambrian age in the Canadian Shield consist of chlorite-albite-carbonate schists, a product of low-rank metamorphism such as can be produced by the deformation of a basalt. The Uchi volcanics represent a distinctly higher metamorphic facies than is common in most greenstones, and which is thought to be the result of igneous intrusion.

The more massive and thicker gabbro sills may have been altered to hornblende-bearing rocks by deformation, but have been further changed by later igneous emanations. The thinner basic flows, which were originally altered to chlorite schists by the deformation accompanying regional folding, have been subsequently changed by igneous metamorphism to hornblende schists. These alterations have locally been somewhat obscured by the superimposition of hydrothermal alteration on the hornblende-bearing rocks, resulting in the development of abundant clinozoisite and carbonate.

The basic members of the Uchi series and the metagabbro adjacent to the Perrigo Lake granodiorite have undergone an intense mineral reconstitution. In the contact zone the rocks are composed of fresh zoned calcic oligoclase and compact hornblende, occurring in a coarse, granoblastic texture. Preëxisting schistosity has been entirely obliterated by the growth of a new massive structure. Farther from the contact to the west and southwest, the hornblendes tend to become more fibrous, the feldspars give way to saussurite and, on the whole, the rocks have a schistose structure. This condition is representative of a large part of the basic rocks throughout the Uchi series, the hornblendes in many instances occurring as metacrysts.

Secondary biotite was observed in nearly all of the basic rocks, where it commonly replaces hornblende and chlorite. In the feldspathic tuffs and breccias and even in some of the thin rhyolite flows small amounts of hornblende have been developed but, more particularly, secondary biotite. Barrell (7) found at the border of the Marysville batholith in Montana that the replacement of hornblende by biotite was due to hydrothermal metasomatism at temperatures only slightly lower than at the contact of the batholith itself. This type of biotitization is widespread in the Uchi volcanics and is considered due to thermal metasomatism. This feature is considered in more detail in connection with wall rock alteration.

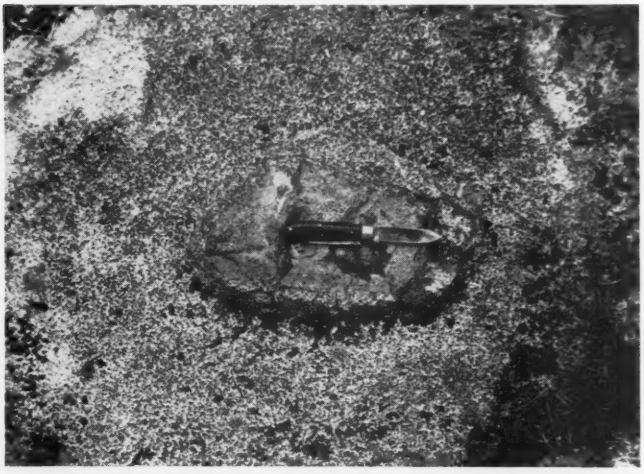


FIG. 6. Greenstone inclusion in Perrigo Lake granodiorite. Note peripheral concentration of hornblende at lower edge of inclusion, and the row of hornblende crystals in the granodiorite above the inclusion.

West of Uchi Lake the hornblende content of the flows is largely replaced by clinozoisite or epidote, and some of the rocks contain such a high content of clinozoisite and carbonate that, in the field, they bear a superficial resemblance to rhyolite flows al-

though having the composition of basalt. A chemical analysis was obtained from a dense, light-colored rock of this character, the following constituents being reported:

		Norm	
SiO_2	45.44	Quartz	0.96
Al_2O_3	20.33	Orthoclase	2.78
Fe_2O_3	3.07	Albite	19.39
FeO	5.40	Anorthite	43.65
MgO	4.76	Diopside	1.36
CaO	12.12	Hypersthene	17.84
Na_2O	2.33	Magnetite	4.41
K_2O	0.45	Ilmenite	0.91
TiO_2	0.52	Apatite	0.34
P_2O_5	0.04	Calcite	5.00
S	tr.	Unused (H_2O)	3.23
CO_2	2.20		99.87
H_2O	3.23		
	99.89	Symbol: II.5.4.5	

W. F. Green, analyst.

The norm as calculated from the chemical composition indicates that the rock belongs to a chemical family of basalts. The mineral composition of the rock is estimated from thin sections as follows:

	Per cent
Clinozoisite and zoisite	45
Epidote	5
Untwinned albite (secondary)	25
Secondary amphibole needles	20
Ilmenite, leucoxene, pyrite, biotite	5
	100

This rock, as well as similar flows in the district that show pillow structure, occurs a mile west of the Uchi gold mine and, as far as is known, is the altered equivalent of the surrounding hornblende schists. The alteration of this type to clinozoisite-rich and carbonate-rich rocks occurs in the vicinity of the gold-bearing quartz veins and is thought to be essentially hydrothermal in origin, and later than the igneous metamorphic development of the hornblende-bearing rocks.

The few basic flows that are exposed to the south and west of

Fly Lake consist mostly of chlorite-albite-carbonate schists, partly replaced by epidote or clinozoisite. These are the only rocks in the district in which secondary biotite has not been recognized, any biotite present being a pathologic-appearing green variety altering to chlorite.

The distribution of the alteration described here results in a broad metamorphic zoning westward from the loci of most intense metamorphism adjacent to the intrusives in the northeast part of the district, the innermost zone being characterized by crystalloblastic oligoclase and hornblende in the basic rocks, the intermediate zone being represented by hornblende-saussurite mixtures, and the outer zone by chlorite. The gold occurrences, in distribution, are confined to a belt near the western border of the hornblende-saussurite zone and within the eastern border of the later zone of clinozoisite-carbonate alteration. The dike rocks are most abundant in the innermost zone of moderately high rank rocks and become less numerous in each of the outer zones.

The recognition and delineation of this metamorphic zoning leads to two conclusions. The first is that, owing to the relation of the metamorphism to the granitic intrusives and their satellites, the higher rank metamorphism in the district is the result of igneous intrusion, and was not brought about by the effects of temperature and pressure accompanying deformation during folding. Thus, before the intrusion of the granites, the greenstones were essentially chlorite schists. The second conclusion, which is supported by the distribution of the dike rocks, is that the boundaries separating the different metamorphic zones roughly contour the upper surface of an underlying granite mass. This conclusion is based on the assumption that the intensity of metamorphism at any one place (other factors being equal) is the resultant of the vertical and horizontal distances from the granite roof. The contouring thus indicates that the granite roof slopes off to the south and west.

Most of the dike rocks are earlier than the period of quartz and gold deposition, but the one group of post-mineralization dikes, which are basic in composition and superficially resemble

lamprophyres, are carbonatized in the vicinity of the veins. These dikes strike in all directions and dip at various angles, some of them being flat-lying. They intersect the quartz veins and orebodies and contain no traces of gold. The freshest specimens of the dikes at some distance from the veins show considerable alteration, being composed principally of bytownite, biotite, and tremolite but, in the vicinity of the orebodies, they consist essentially of carbonate (ankerite and calcite) and secondary albite-oligoclase. This alteration, which parallels that of the adjacent wall rock, indicates that although the dikes were introduced after the time of gold deposition, it was before the final cessation of mineralizing solutions, which were still sufficiently potent to attack the dikes adjacent to the veins. This association of gold with the dike rocks is strong evidence in favor of a genetic origin from the subjacent granite, probably during the late stages of consolidation of the underlying intrusive, and the evidence is strengthened by the indications that the dikes were introduced before the mineralizing action had ceased.

CHARACTER OF THE GOLD DEPOSITS.

Most of the gold occurrences in the district are distributed in a north-south belt that has been traced southward from the east side of Lost Bay of Confederation Lake to near the south end of Uchi Lake. As these deposits are described in more detail elsewhere,[3] they will be mentioned briefly. The geology of the gold-bearing section consists of narrow interbedded greenstone flows, metagabbros, tuffs, and silicic flows in approximately vertical positions, striking northward and pitching to the south. These rocks, because of their variable degree of resistance to stresses, have fractured along or near the contacts, thus providing channelways for vein-forming solutions. Similar structural conditions may be found wherever there is a variety of rock types, and gold deposition seems to have shown a predisposition for moderately brittle rocks that fracture well than for shear zones. The gold deposits are, therefore, associated with open space fillings,

[3] Ann. Rept., Ont. Dept. Mines, vol. 38, 1039.

although major orebodies consist of country rock replacements adjacent to tension fracture, quartz stringer zones. The gold is in the native state and may occur in the quartz or in the adjacent country rock, which is commonly mineralized with disseminated metasomatic pyrite and pyrrhotite. There are earlier sulphide replacement zones in shear zones, but these do not appear to be related to the later sulphides associated with the orebodies.

WALL ROCK ALTERATION.

A comparison of the altered wall rock in the vicinity of the veins and orebodies with the less altered greenstones a short distance from the veins indicates a profound alteration in which the hornblende and epidote have disappeared and the rock has become extensively replaced by carbonate, sericite, pyrite, pyrrhotite, biotite and albite in quantitative order. A chemical analysis of the fresher greenstone is compared with one of the altered wall rock from the same flow.

	1.*	2.†
SiO_2	50.65	36.60
Al_2O_3	14.57	13.01
Fe_2O_3	2.31	2.15
FeO	11.59	7.41
MgO	4.34	4.48
CaO	6.70	8.78
Na_2O	2.45	2.76
K_2O	0.59	3.28
TiO_2	1.31	1.31
P_2O_5	0.11	0.04
MnO	0.32	0.09
H_2O	2.67	2.03
CO_2	2.40	9.90
FeS_2	0.28	8.04
	100.29	100.08
	Sp. Gr. 2.82	Sp. Gr. 2.854

W. F. Green, Analyst.

* Greenstone country rock.

† Hydrothermally altered equivalent in the orebodies.

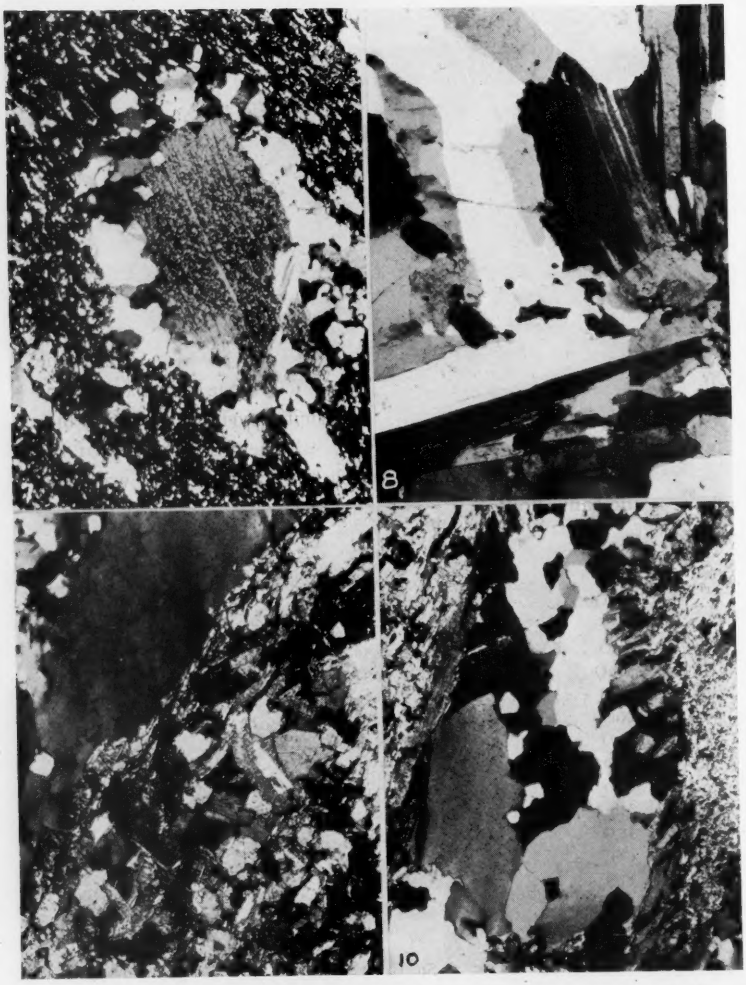


FIG. 7. Amygdaloidal greenstone near orebody in Uchi gold mine, showing a vesicle filled with carbonate (grey with twinning striae) and rimmed with quartz (white). x nicols; × 40.

In addition to showing a remarkable desilication, a comparison of the analyses shows substantial increases in lime, potash, carbon dioxide and hydrogen sulphide. Potash shows the greatest percentage gain in grams per cubic centimeter and has, for the most part, been taken up in the formation of biotite and sericite. Fig. 7 shows an amygdule in the altered carbonatized amygdaloidal greenstone which is filled with carbonate and collared by quartz.

Carbonatization is a common wall rock alteration in hydrothermal mineral deposits. In the Uchi Lake area, much of the carbonate of the wall rock is calcite although some ankerite is present. In the veins, calcite and ankerite are present in approximately equal proportions. Calcite has been observed replacing ankerite in many instances, and most of it is presumed to be later. The wall rock carbonatization has advanced to the extent that as much as 75 per cent or more of the greenstone is composed of carbonate. Adolph Knopf (8) has described a somewhat similar type of alteration in the Mother Lode district of California, where there is a widespread replacement of greenstone by ankerite to the extent that, near the veins, the greenstones are almost solid ankerite. Additional wall rock alteration in the Mother Lode district consists of the formation of sericite, albite and pyrite; a notable lack of silicification was emphasized. This occurrence parallels the Uchi Lake district, except for the abundance of secondary biotite in the latter locality.

The alteration of the country rock in the Uchi Lake district is principally metasomatic. The ankerite was formed by the addition of carbon dioxide from vein forming solutions, the carbon dioxide combining with original lime, magnesia and iron in the rock. Additional iron was taken up by an excess of hydrogen sulphide to form disseminated pyrite and pyrrhotite, and some

FIG. 8. Vein quartz from Uchi gold mine showing large grains of albite. x nicols; × 40.

FIG. 9. Vein quartz (in extinction) in contact with the carbonatized and biotitized wall rock in the Uchi gold mine. x nicols; × 40.

FIG. 10. Photomicrograph microveinlet of quartz in carbonatized wall rock in Uchi gold mine. The veinlet is bordered with biotite, a common feature in the district.

later ankerite was formed by the replacement of these sulphides. Calcite was formed in the country rock after most of the iron had been used up, and it is probable that the vein-forming solutions did not contain much iron in the early stages. The appreciable addition of potash resulted in the formation of sericite and biotite and, although the increase in soda is slight, large clear grains of albite (Fig. 8) having the composition $Ab_{96-97}An_{3-4}$ occur in the vein quartz. As in the case of the Mother Lode district, there is a notable lack of silicification in the Uchi gold area and even the wall rock inclusions in the quartz veins tend to be carbonatized rather than silicified. This carbonatization of the country rock implies a desilication that has resulted in the removal of considerable quantities of silica. Throughout the Canadian Shield many gold deposits are characterized by silicification of the wall rock that accompanied quartz vein deposition; thus a case such as this, which is the opposite condition, deserves emphasis. The accompanying photomicrograph (Fig. 9) shows the carbonatized and biotitized wall rock in sharp contact with vein quartz (in extinction).

The mineralizing solutions, in addition to silica, contained carbon dioxide, potash, hydrogen sulphide and soda, and at one stage, iron. Throughout the process of mineralization the solutions changed in composition. Small amounts of copper were introduced and, towards the close of mineralization, minute amounts of lead and zinc were brought in with the gold. The process of carbonatization appears to have started early and continued through to the very end, as the post-metallization dikes are extensively carbonatized near the orebodies. Early formed carbonate is replaced by quartz that is, in turn, replaced by carbonate. Biotite commonly replaces sericite and carbonate.

The presence of biotite and albite in the veins (Fig. 10) as well as in the wall rock is taken to indicate relatively high temperatures during at least one stage of the mineralization. Albite accompanies the formation of many gold-quartz veins that are thought to be of high temperature origin, and Schwartz (9) has suggested that its secondary formation occurs under temperatures favoring

dehydration. The untwinned variety, however, is a common accompaniment of the low rank green schists. Biotitization is widespread in the Uchi volcanics and its presence in originally potash-poor rocks favors the addition of potash from solutions derived from an underlying granite. The development of secondary biotite, however, is not common in connection with the wall rock alteration of hydrothermal gold-quartz veins in general, but it has been reported in the Juneau district by Spencer (10) and in the Eagle River district by Knopf (11), these workers accepting it as an indicator of the addition of potash. In the Berens River gold-silver mine at Favourable Lake in northwestern Ontario, the writer (12) observed intense biotitization connected with wall rock alteration. The altered rhyolite country rock in the vicinity of the orebody is extensively silicified, and the interbedded more basic flows are not only silicified, but contain up to 20 per cent metasomatic biotite as well as garnet. The quartz veins, a combination of fracture filling and replacement, contain garnet, actinolite, arsenopyrite, and pyrite—a high temperature combination, particularly when considered with the nature of wall rock alteration. The wall rock alteration, however, does not appear to have any direct connection with the metallization at the Berens River mine, sphalerite, galena, tetrahedrite, gold and silver being introduced at a later time and probably at a considerably lower temperature, although the entire sequence may have been a continuous one of falling temperature.

Biotitization in the Uchi Lake district followed the initial carbonatization and appears to have been approximately contemporaneous with the deposition of albite and pyrrhotite in the vein quartz. This was followed by the deposition of chalcopyrite, a second generation of pyrite and a fracturing of the vein quartz and walls, the gold being introduced at a later stage. Thus, although the wall rock alteration is approximately confined to the orebodies, the changes had taken place largely before the time of introduction of the gold. After the metallization had occurred a new set of fractures developed in a complicated pattern, along which arose the basic magma of the post-vein dikes.

CONCLUSIONS.

1. The intrusion of the granitic rocks that represent the close of Archean time in the Uchi Lake district resulted in profound alterations on the invaded rocks that are, in part, indicated by a metamorphic zoning throughout the district.

2. The known gold occurrences lie in a belt near the outer border of the hornblende-saussurite zone, where the rocks have undergone a further hydrothermal alteration characterized by clinozoisite, indicating a relationship between gold deposition and granitic intrusion. Evidence for this relationship is strengthened by the relation of the dike rocks to the gold-bearing quartz veins. The fractures in which the veins were formed intersect earlier dike rocks, the veins themselves being intersected by later basic dikes.

3. The widespread biotitization of the rocks in the district and of the orebodies in particular both indicate the addition of potash from a common source—an underlying granitic magma. The development of biotite and the carbonatization of the wall rock present a striking contrast with many Canadian gold deposits, where silicification and the addition of soda is emphasized in connection with gold deposition.

4. The distribution of dike rocks and metamorphic zoning indicates that the roof of the underlying granite, although irregular, slopes off to the southwest, and is not in the form of a cupola beneath the gold-bearing zone. Deposition of gold occurred at a favorable horizon above the granitic magma roof where temperature and pressure conditions probably played an important part in precipitating the precious metals; but the principal factor favoring deposition is a structural one based on the ability of the rocks to fracture and thus provide channelways for solutions.

5. Granitic invasion, metamorphism, introduction of silicic dikes and porphyries, formation of barren quartz veins, wall rock alteration, metallization, and intrusion of post-vein dikes are all part of a magmatic sequence of falling temperature. Towards the end of this sequence the gold was deposited, the solutions being derived from a late differentiate of the consolidating magma.

Although the deposits are hydrothermal in origin, they cannot be properly classified as hypothermal or mesothermal. The reason for this is that the wall rock alteration and deposition of most of the sulphides, being early in the sequence, may be of high temperature origin; but the gold, being later, may have been deposited at relatively low temperatures. The precious metals, therefore, may bear no necessary relation to the associated gangue minerals.

ACKNOWLEDGMENTS.

This paper summarizes portions of a dissertation, presented for the degree of Doctor of Philosophy in Yale University. The writer wishes to thank Professors Alan M. Bateman and Adolph Knopf for their generous assistance during this work. The field studies were carried out during geological field work for the Ontario Department of Mines, and the writer is indebted to Dr. M. E. Hurst, Provincial Geologist, for permission to publish the results.

CREIGHTON MINE, ONT.,
August 17, 1939.

BIBLIOGRAPHY.

1. BRUCE, E. L.: Geological relationships of some major gold deposits in the Canadian Shield. A. I. M. E. Tech. Pub. 807, 1937.
2. HENDERSON, J. F., AND JOLLIFFE, A. W.: Relation of gold deposits to structure, Yellowknife and Gordon Lake areas, Northwest Territories. Can. Inst. Min. & Met., Trans. 42: 314–336, 1939.
3. BRUCE, E. L.: Structural relations between some gold deposits between Lake Nipigon and Long Lake, Ontario. ECON. GEOL., 34: 357–368, 1939.
4. THOMSON, J. E.: Geology of the Uchi Lake area. Ont. Dept. Mines, 37: pt. 3, 1938.
5. CORNELIUS, H. P.: Zur Frage der Beziehungen von Kristallisation und Schieferung in metamorphen Gesteinen. Centralblatt für Mineralogie, 1921, pp. 1–11.
6. HUTTON, C. O.: A chemical and optical study of a low-grade metamorphic actinolitic amphibole from Coronet Peak, western Otago, New Zealand. Miner. Mag., 25: 207–211, 1938.
7. BARRELL, J.: Geology of the Marysville mining district, Montana. U. S. Geol. Surv., Prof. Pap. 57, 1907.

8. KNOPF, A.: The Mother Lode system of California. U. S. Geol. Surv., Prof. Pap. 157, 1929.
9. SCHWARTZ, G. M.: Hydrothermal alteration of igneous rocks. Geol. Soc. Amer., Bull. 50: 181–238, 1939.
10. SPENCER, A. C.: The Juneau gold belt, Alaska. U. S. Geol. Surv. Bull. 287, 1906.
11. KNOPF, A.: The Eagle River region, southeast Alaska. U. S. Geol. Surv. Bull. 502, 1912.
12. BATEMAN, J. D.: Recent developments in the Favourable Lake area. Ont. Dept. Mines, 47, pt. 7: 79–92, 1938.

PHOSPHATE DEPOSITS OF THE UNITED STATES.[1]

GEORGE R. MANSFIELD.

ABSTRACT.

Different types of phosphate deposits and different sources of phosphate in the United States are briefly discussed. In Florida two types of phosphate are now mined, land pebble and hard rock. The principal characteristics of these types of rock are stated and methods of prospecting, mining and recovery briefly outlined. Testimony given before the Congressional Committee to Investigate the Adequacy and Use of Phosphate Resources of the United States, November 28, 1938, at Lakeland, Fla., showed Florida's reserves to be far greater than previously supposed. Similarly at corresponding hearings in Tennessee a few days earlier the reserves of brown phosphate, the only type now mined in that State, were shown to exceed earlier official estimates. Reserves of the Western fields have been raised a little to bring them abreast of current information but no attempt has been made, as in the other States named, to include lower grades of rock than those formerly considered in the estimates. Professor J. Stewart Williams has shown for Utah that such a procedure would tremendously increase these figures.

Reserves of the United States as a whole are now considered to exceed ten billion tons, not counting those classed as possible or certain phosphatic limestones mentioned at the hearings of the Congressional Committee. As nearly 2,000,000 acres of public land in the Western States and 66,000 acres in Florida remain to be examined for their phosphate content the stated figure will ultimately be greatly increased. At the present rate of consumption, 3,000,000 tons annually, ten billion tons would last more than 3,000 years.

CONTENTS.

Abstract 405
Character and distribution 406
South Carolina field 408
Types of rock 408
Origin 409
Quality 410
Production and reserves 410

[1] Address delivered before the Association of Land Grant Colleges and Universities, Logan, Utah, September 2, 1939. (Published by permission of the Director, Geological Survey, U. S. Department of the Interior.)

Florida field 411
Land pebble deposits 412
General character—main field 412
Other areas 412
Prospecting 412
Mining and washing 413
Phosphate content of matrix 413
High grade phosphate 414
Reserves 414
Hard rock deposits 414
General character 414
Distribution 415
Relation to structure 415
Prospecting 415
Mining and processing 415
Reserves 416
Soft rock 416
River pebble deposits 416
Hawthorn formation and phosphatic marl 416
Summary of phosphate reserves in Florida 417
Tennessee field 418
Distribution 418
Brown, Blue and White rock 418
Reserves 420
Kentucky field 422
Arkansas field 422
Western field 423
Geologic age 423
Mode of occurrence 423
Stratigraphic character and relations 425
Prospecting 426
Mining and beneficiation 426
Phosphate land classification 426
Reserves 428
Summary of phosphate reserves of the United States 429

CHARACTER AND DISTRIBUTION.

THE principal types of phosphate deposits found in this country are guanos, apatites, phosphatic marls and limestones, and phosphate rock representing a wide range in geologic age.

The guanos, which are cave deposits and consist of the excreta

of bats and other animals, have been reported chiefly from Texas and New Mexico, where they have or have had local commercial importance in a small way. The Texas product contains 4 to 12 per cent of ammonia together with nearly 4 per cent of available P_2O_5, and 1.25 per cent of potash. Some of the New Mexico material is richer and is reported to contain as much as 32 per cent of P_2O_5 with 28 per cent available.[2]

Phosphatic marls occur in the sedimentary rocks of the Coastal Plain from the Middle Atlantic to the Gulf States and are of both Cretaceous and Tertiary age. Ordinarily they contain from less than 1 to 4.5 per cent or more of P_2O_5. Exceptionally, as in Alabama, concretions in the marl contain 20 to 30 per cent of P_2O_5.[3] Before the introduction of commercial fertilizers marls were dug at many places and used by farmers for direct application to their soils.

Phosphatic limestones are widely distributed in both the eastern and western parts of the United States and range in age from early Paleozoic to Tertiary. The percentage of P_2O_5 that they carry is ordinarily small, though some of them, which have served as parent rocks of phosphate deposits, contain notable amounts and may deserve future consideration as potential sources of commercial phosphate products.

Apatite is a phosphatic mineral widely distributed as a constituent of igneous and metamorphic rocks, but it is rarely accumulated in any one place in sufficient quantity to be of economic interest as a source of commercial phosphates. The Russian apatite deposits now being extensively exploited are a notable exception. In the United States the only apatite deposits in production are those of Nelson County, Va., which are being mined with associated titanium minerals. The amount produced is not disclosed, as there is only one producer, and figures given in the Minerals Yearbook are combined with those of Tennessee.

Phosphate rock deposits are grouped in a number of separated areas in which the character of the deposits and the methods of

[2] Phillips, W. B.: The bat guano caves. Mines and Minerals, 21: 440–442, 1901.

[3] Smith, E. A.: The phosphates and marls of Alabama. A. I. M. E. Trans. 25: 819–820, 1895.

operation differ so that it is customary to regard them as separate fields. In the United States nine phosphate fields deserve mention as being active or potentially active, namely, North Carolina, South Carolina, Georgia, Florida, Tennessee, Kentucky, Alabama, Arkansas, and the Western phosphate field.

The North Carolina,[4] Georgia,[5] and Alabama[6] fields have yielded little commercial phosphate and have not been sufficiently explored to permit any estimates of quantity to be made, though it is known that the phosphates are relatively poor as compared with the Florida and Tennessee material. The other fields will be described briefly in the order named.

SOUTH CAROLINA FIELD.[7]

Location.—The deposits of phosphate in the vicinity of Charleston, S. C., were among the first discovered in the United States, and for a time South Carolina was one of the largest producers in the world. The workable deposits are confined to the region lying in general between Charleston and Beaufort and extending about 25 miles back from the coast, Fig. 1. The phosphate rock occurs as an irregular, thin bed, that underlies irregular areas in the region defined. This bed is commonly less than 18 feet below the surface, and is thus comparatively easy to mine, but because of the low grade of the rock and the exploitation of the richer and more easily accessible deposits of Florida and Tennessee, production in the South Carolina field ceased. Recent attempts to revive activity there have thus far accomplished little.

Types of Rock.—Two types of rock are recognized—land rock and river rock. The land rock occurs in an irregular bed 8 to 16 inches, or, locally, as much as 30 inches thick. The rock is an irregular or even jagged, honeycombed mass that breaks easily on mining and is thus commonly referred to as nodular. It

[4] N. Car. Exp. Sta. Bull. 110, 1894.

[5] McCallie, S. W.: A preliminary report on a part of the phosphates and marls of Georgia. Georgia Geol. Surv. Bull. 5, 1896.

[6] Smith, E. A., and McCally, H.: Index to the mineral resources of Alabama. Ala. Geol. Surv., 1904, pp. 64, 65.

[7] Rogers, G. S.: The phosphate deposits of South Carolina. U. S. Geol. Surv. Bull. 580: 183–220, 1915.

varies in hardness, specific gravity, and color with degree of phosphatization, the better rock being generally darker colored. The river rock occurs in loose, more or less rounded fragments

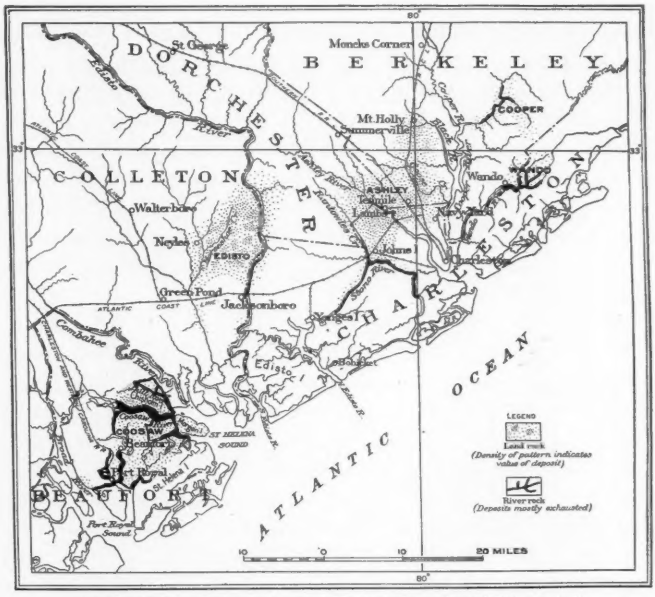


FIG. 1. Map showing approximate original distribution of South Carolina phosphate deposits.

of nodular aspect, accumulated with some matrix of mud or sand in irregular banks on the bottom.

Origin.—Numerous theories for the formation have been advanced. The view advocated by Rogers,[8] which seems to account satisfactorily for all the facts, is that the phosphate represents a residual deposit of Cooper marl (Eocene) reworked and redeposited as the Edisto † marl[9] (now called Hawthorn) in Mi-

[8] Rogers, G. S.: op. cit.

[9] A dagger (†) following a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the Federal Geological Survey.

ocene times and subsequently concentrated and enriched by solution.

Quality.—The commercial rock varies greatly in chemical composition but does not ordinarily exceed 64 per cent of tricalcium phosphate (bone phosphate of lime or B. P. L.). The average composition of South Carolina phosphate, as compiled by Shepard,[10] on the basis of many hundred analyses, is about 58 per cent of B. P. L. The rock is lower in phosphate content than the Florida or Tennessee products but possesses certain advantages for the fertilizer manufacturer. After calcining it grinds readily and cheaply into an impalpable powder, which allows sulphuric acid to act uniformly on the whole mass. The superphosphate formed is light, dries readily, and remains in good mechanical condition for mixing.

Production.—Production of river rock ceased in 1910 and of land rock in 1925. The total production from the field from 1867 to 1925, according to Mineral Resources reports, was 13,357,108 tons. In 1938 an additional 100 tons of 60–66 per cent grade was shipped.

Reserves.—In his account of the South Carolina phosphates, Rogers[11] modifying an earlier (1904) estimate of Chazal, figured the reserves of land rock at between 7,000,000 and 9,000,000 tons. No estimates are available for the river rock. In 1925[12] I adopted the higher figure, which, after allowance for rock mined during the interval, became 8,800,000 tons. In 1938 Jacob[13] by similar means reduced this estimate to 8,798,000 tons. The original figures from which these were derived were based on the best data available at that time. No doubt they need revision and if modern methods of prospecting and laboratory testing were employed it seems probable that they might be greatly increased, especially if river rock is taken into account. As no

[10] Shepard, C. U., Jr.: South Carolina phosphates. Charleston, S. C., 1880.

[11] Rogers, G. S.: Phosphate deposits of South Carolina. U. S. Geol. Surv. Bull. 580: 202, 1914.

[12] Mansfield, G. R.: Phosphate rock in 1924. Bur. Mines, Min. Resources of the U. S., 1924, Pt. II, p. 88, 1925.

[13] Jacob, K. D.: The phosphate rock reserves of the United States. Commercial Fertilizer Yearbook, 1938, p. 10.

commercial pressure exists for their further exploitation it seems unlikely that the necessary prospecting will be undertaken for a long time.

FLORIDA FIELD.

Florida is the leading State in the production of phosphate rock and much has been written about its deposits. Reference to

FIG. 2. Map of Florida showing distribution and character of phosphate deposits. Hard rock data from Eldridge (11th Census) and W. L. Akin; pebble and outlying areas, Wayne Thomas; Hawthorn, Fla. Survey 20th Ann. Rept.

most of these articles may be had in the bibliographic bulletins of the Geological Survey [14] and in the Annotated Bibliography of Economic Geology.[15] The principal types of rock in the order of their present relative commercial importance are the land pebble, hard rock, soft rock, and river pebble (Fig. 2).

Land Pebble Deposits.

General Character—Main Field.—The land pebble phosphate is contained in the Bone Valley gravel of Pliocene age. This is of shallow water estuarine and marine origin and its phosphate was derived largely from phosphatic limestones of the Hawthorn formation of Miocene age by erosion and redeposition, although some material from contemporary sources is included. The matrix contains in addition to the phosphate pebble much clay and sand. It is irregularly bedded, ranges in thickness from less than a foot to nearly 25 feet, and lies on a fairly even floor of clay or limestone. It varies from place to place in relative proportion of coarse and fine material and in phosphate content. The overburden consists largely of sand and clay and may range well over 50 feet in thickness, although, where mined, it is generally less than that.

Other Areas.—In addition to the main pebble field, which is located chiefly in western Polk County and adjacent parts of other counties, land pebble phosphates have been found in Hamilton, Clay, Bradford, Lake, and Orange Counties. On some of these prospecting work has been done. Hitherto their high silica content has made them appear of low grade and commercially unattractive. The advent of flotation has changed this picture notably for it has been found that by grinding and flotation, high grade phosphate may be developed from some of them.

Prospecting. In prospecting the pebble field a modified form of post hole auger is used and each hole is cased. Thorough prospecting of a 40-acre tract involves generally boring 16 holes. These are regularly spaced according to a grid indicated by letters

[14] U. S. Geol. Surv. Bulls. 746, 747, 823, 834, 858, 869, 892. See also Bull. 604.
[15] Ann. Bib. Econ. Geol. Gen. Index. I–X, 1928–1938, Econ. Geol. Pub. Co., 1939.

and numbers. The data for each hole in this spacing are applied to 2½ acres. In preliminary prospecting work 8-hole or even 4-hole work may suffice for some purposes. The selection of minable areas from prospecting data requires care to exclude those holes that show too low tonnage per acre, too high a percentage of iron and alumina, too high a flotation ratio (the ratio between the total tons of rock recovered and the number of tons treated by the flotation plant), and too high a ratio between overburden and available rock. Thus, even some holes that show fairly high grades of B. P. L. (70 per cent or more) may be excluded. Accordingly the number of acres considered minable in a given prospected tract is usually smaller than the number prospected.

Mining and Washing.—Mining pebble phosphate involves first the removal of overburden, generally by dragline, and piling the waste alongside of the area to be mined or in mined out areas. Care is taken to avoid so far as possible covering up areas underlain by minable rock. The matrix itself is mined by hydraulic methods and the rock pumped through pipe lines to the washer, which may be as much as a mile distant. In the washing plants finer sized material is saved than formerly, and in some plants a flotation process is added to reduce losses still further. The soft phosphate and finer waste materials washed from the matrix are allowed to settle in waste ponds where they may later be available if needed.

Phosphate Content of Matrix.—The phosphate content of the matrix as it comes to the plant is not high. Matson[16] cites an analysis of matrix in which the B.P.L. content is about 30 per cent. This may not be truly representative as the sample was small. However, I am informed that the matrix generally contains 15 to 40 per cent B. P. L. and that 35 per cent is about the most favorable for material to yield the products of greater value. When the matrix contains 40 per cent or more of B. P. L. so much of the material will go into slime that much of the higher grade portion will be lost. High grade phosphate, therefore, does not occur as such in the ground. Although the amount available in a given

[16] Matson, G. C.: The phosphate deposits of Florida. U. S. Geol. Surv. Bull. 604: 82, 1915.

area may be forecast by selective prospecting the actual segregation of high grade rock for stock piles or immediate shipment comes at the end of a long and chemically controlled beneficiation process.

High Grade Phosphate.—In practice high grade rock must contain 74 per cent of B. P. L. although rock of lower grade is exported under some contracts. Rock of this quality, although more desirable for use in the acidulation process because it requires less sulphuric acid and less handling than lower grade material, is less desirable for use in the electric furnace because silica and other substances removed in its production must be added again for fluxing. Thus, it would probably be cheaper and more satisfactory to select for furnacing a deposit in which the matrix contains about the right proportions of silica and lime for fluxing purposes and to improve its phosphate content by adding more or less higher grade material to the mix.

Reserves.—At the hearings of the Congressional Committee in Lakeland, November 28–30, 1938, much new data on Florida phosphate reserves were presented that had not hitherto been made available. Through the courtesy of the producers, especially of D. B. Kibler, Jr. of Lakeland, Manager of the Buttgenbach Phosphate Co., and of Wayne Thomas of Plant City, principal witness for the industry at the hearings, I have been able to study much of this material and have spent several months in preparation of a report on the phosphate resources of Florida. In general I have tried to differentiate grades and to classify the reserves as known, probable, or possible. Space does not permit a detailed review of this work but I may say that it served largely to substantiate the figures given at the hearings for the different areas of land pebble and hard rock phosphate. The results are summarized in a table that follows the discussion of the other Florida phosphates.

Hard Rock Deposits.

General Character.—The hard rock deposits are contained in the Alachua formation of Pliocene age. They are residual deposits and, like the Bone Valley gravel, were derived from phosphatic

limestones of the Hawthorn formation. But unlike the Bone Valley gravel they were not subjected to marine erosion and rearrangement. They are the end products of successive accumulations formed by the leaching of limestone and of the deposition and redeposition of phosphatic materials. In general they are heterogeneous mixtures of fragments and boulders of phosphate rock ranging from less than an inch in diameter to masses weighing several tons, together with sand, clay, chert, and soft phosphate. In places they also include bedded materials.

Distribution.—The hard rock deposits lie in a belt 5 to 30 miles wide extending southeastward from the vicinity of Tallahassee to the northern part of Pasco County, roughly 150 miles.

Relation to Structure.—The Florida peninsula has been arched into an elongate dome, the axis of which lies somewhat west of the center line of the peninsula. It is in this structure that the Hawthorn formation has been raised sufficiently to permit deep and prolonged erosion and the residual accumulation of its phosphate in favorably situated areas.

Prospecting.—Much of the potential phosphate land in the hard rock field has not been prospected by modern methods. On the other hand some areas previously regarded as mined out have been reprospected and re-mined with the result that tonnages greatly exceeding those obtained by earlier work have been recovered.

Thorough prospecting in the hard rock field involves boring 16 holes to the acre in contrast to the pebble field where 16 holes ordinarily suffice for 40 acres. Prospecting costs in the hard rock field are, therefore, higher than in the pebble field. Sixteen hole work requires a 50-foot spacing between holes. In preliminary prospecting 100-foot spacing may suffice but for guidance in mining it is at times desirable to use a 25-foot interval and rarely even 12½ feet. The closer spacing in the hard rock field is required by the highly irregular surface of the bed rock on which the matrix rests. The position of the holes and the data obtained from them are recorded in grids on plats or maps and these are closely followed in mining.

Mining and Processing.—In mining the hard rock hydraulic methods are used to remove the overburden and the matrix is

taken out by dragline machines, which are able to excavate the deep depressions and crevices. As the deposits are more localized the washing plants are smaller than those in the pebble field. Much more fine material is saved than formerly, although flotation is not used. Comparable results are obtained, however, by sizers and tables. Here again the high grade rock is a product of controlled beneficiation.

Reserves.—The reserves in the hard rock field, though substantial, are rated in my study considerably lower than the figures given at the Lakeland hearings. They are shown in the table already mentioned.

Soft Rock.

A certain amount of finely divided phosphatic material, soft rock, is present in both the land pebble and hard rock fields, although the amount varies locally. It is too fine to be caught on screens or floated, and passes with the slimes to the waste ponds, from which it is being mined in some places and sold for direct application to the soil or as filler in fertilizer mixtures. Soft rock is included as possible reserves in the figure given for the hard rock field, though it is not separately listed.

River Pebble Deposits.

River pebble phosphate, as the name implies, occurs as bars and banks in stream channels and neighboring lowlands. It is formed from any phosphatic material that the stream may happen to cross, such as the Hawthorn formation or any deposits derived from it. Hence, much of it may be of recent age. Nearly a million and a half tons of it was mined during the years 1888 to 1908 inclusive. Then, mining stopped not because of the exhaustion of the deposits but because of the competition of more desirable types. As the valleys of Peace River and of other streams known to contain river pebble phosphate cover many square miles, it is reasonable to infer that river pebble rock should have a place in Florida's phosphate reserves.

Hawthorn formation and Phosphatic Marls.

It was brought out at the hearings in Lakeland that the Hawthorn formation, the parent rock of most of the phosphate de-

SUMMARY OF PHOSPHATE RESERVES IN FLORIDA.

Type or Field.	Acres.	Grade Per Cent.	Known Long Tons.	Probable Long Tons.	Possible Long Tons.	Remarks.
River pebble		55 ±	5,000,000	15,000,000	30,000,000	Rounded figures throughout.
Land pebble						
Hamilton County	14,000		1,000,000	24,000,000	25,000,000	77 per cent grade possible by crushing and flotation.
Clay County					90,000,000	Similar to deposits of Hamilton County.
Bradford County					55,000,000	May be Hawthorn. Grade may range up to 70.
Lake and Orange Counties					100,000,000	Grade 55 or better?
Main field	675,000	74 +	130,000,000	315,790,000	315,790,000	
		70–74	1,870,000,000			
(Bone Valley gravel.)	565,000	55–70		141,250,000	423,750,000	
Hard rock						
Main field	120,000	65 +	41,281,000	580,108,000	417,970,000	
		40–65	10,702,000	150,398,000	337,400,000	
Steinhatchee district	3,000		600,000	600,000	1,200,000	
	1,377,000		2,058,583,000	1,227,146,000	1,796,110,000	

Total known, probable, and possible tons in areas considered, all grades, 5,081,839,000 long tons.

posits, is itself sufficiently phosphatic to deserve consideration as a possible future source of commercial phosphate. Similarly certain phosphatic marls were also mentioned. The data now available for these formations are insufficient to justify their present inclusion in reserves, although it is recognized that they are worthy of further consideration and study.

TENNESSEE FIELD.

The phosphate deposits of Tennessee rank next in present commercial importance to those of Florida.

Distribution.—The phosphates occur in the western part of the Central Basin of Tennessee and in the valleys of the western part of the Highland Rim surrounding the basin. The workable beds lie in parts of Sumter, Davidson, Williamson, Lewis, Maury, Hickman, Perry, Giles, and Decatur Counties (Fig. 3). Phosphate has also been found in Johnson County along the east border of Tennessee. Three general classes of phosphate are recognized, namely: brown, blue, and white. Of these the brown rock is at present the most important commercially.

Brown Rock.—The brown phosphates are residual deposits derived from several formations of Ordovician age, consisting largely of limestone that is more or less phosphatic. The gentle arching of the formations into a low dome has permitted erosion to attack them so that percolating surface waters charged with carbonic acid and other organic acids have had access to them. The limestone at some places has been more or less completely removed, whereas the phosphatic and other less soluble constituents of the original rock have been allowed to accumulate. Where these accumulations have formed on relatively low or flat ground they tend to blanket the surface and form so-called "blanket deposits." The floor of limestone on which they lie is very irregular, so the deposits range from nearly nothing to locally as much as 50 feet thick in the deeper depressions or "cutters." The upper part of such deposits becomes leached of phosphate to a greater or less depth and constitutes an overburden that must be removed. The phosphate thus leached tends to be re-

deposited below in what is called the matrix or muck, where it may replace sandy or cherty layers or may enlarge or enrich phosphatic masses already accumulated. Thus, the matrix contains in some places lumps or plates of richer material called plate or lump rock, which has been selectively mined since the beginning of operations

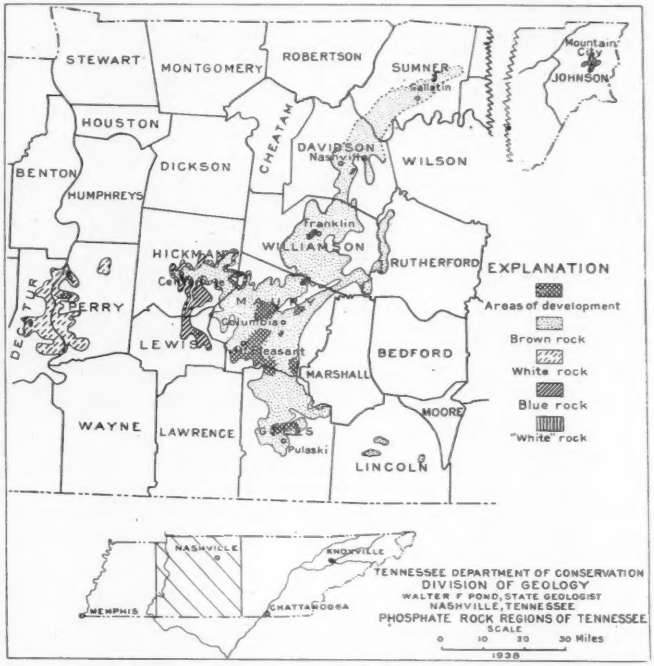


FIG. 3. Map of Central Tennessee, showing distribution of phosphate deposits.

and is now said to be growing relatively scarce. On steeper hillsides brown rock follows the outcrop of its parent formation and makes "rim" or "semi-blanket" deposits but these, when tunneled, soon pass into the unaltered, parent rock and are accordingly less attractive than blanket deposits. Prospecting methods are comparable to those used in the Florida fields.

The Tennessee brown rock, like the Florida material, requires washing and beneficiation to produce the higher grades required for the market. The muck in the ground probably does not exceed 60 per cent in B. P. L. content and much of it runs considerably lower, between 40 and 50 per cent. Matrix containing less than 30 per cent is considered unminable under present conditions.

Blue Rock.—According to testimony given at the hearings of the Congressional Committee at Wilson Dam, Nov. 22, 1938, the blue rock is an unaltered portion of the Hardin sandstone member of the Chattanooga shale of basal Mississippian or Upper Devonian age, occurring in Hickman, Lewis, and Maury counties underlying the edge of the Highland Rim on the southwest side of the central basin. It varies in thickness from a few inches to 3 feet and is locally as much as 6 feet or more thick. In composition it ranges from a somewhat phosphatic shale or sandstone to a highly phosphatic rock containing as much as 75 per cent of B. P. L. and averaging 65 per cent. As it requires underground methods of mining, which are more expensive than the open pit methods commonly used in mining the brown rock, comparatively little of it has been mined.

White Rock.—The white rock deposits, found principally in Perry and Decatur counties, are secondary deposits formed by solution of phosphatic minerals in the overlying blue rock and by redeposition in crevices and openings in the underlying limestones, where they have to a considerable extent replaced chert and limestone. They are accordingly spotty both in distribution and grade. Hand specimens may run as high as 90 per cent or more of B. P. L. but the average of a deposit large enough to mine seldom contains more than 60 to 65 per cent. Only a few thousand tons has been mined.

Reserves.—Jacob,[17] expanding the earlier estimates of Phalen[18] and making allowance for flotation, estimated the Tennessee phos-

[17] Jacob, K. D.: The phosphate reserves of the United States. Commercial Fertilizer Handbook, 1938, pp. 10–14.

[18] Phalen, W. C.: Phosphate rock in 1915. U. S. Geol. Surv., Min. Resources of the U. S., Part II, p. 238, 1916.

phate reserves at 101,364,000 long tons, of which 18,131,000 is brown rock and 83,233,000 blue rock. No estimate was made for white rock.

Testimony before the Congressional Committee, which introduced phosphatic limestones as a part of the reserves, greatly increased the figures just given. The State Geological Survey of Tennessee has been reviewing this testimony and expects to give its version of it in a forthcoming publication.

In response to a letter requesting information about this work, Capt. W. F. Pond, State Geologist, on August 23, 1939, wrote as follows:

> Five of the eight major operators in the State, including Tennessee Valley Authority, have given us their data on their reserves of brown rock. Estimated reserves of the three other companies are possible because of more or less familiarity with their holdings. It is expected that we will get the actual figures from the companies later. . . . The estimates of reserves for the three companies are a comparatively small portion of the total.
>
> Reserve estimates for known brown phosphate deposits on privately owned land include only those that have been personally examined by members of the Tennessee Division of geology, or by other qualified geologists or engineers. A considerable part of the data for these properties has been derived from actual prospecting records.
>
> The reserves of brown rock on company owned and private lands total 86 million long tons, averaging 48 per cent of B. P. L. This estimate is to a considerable extent proved by prospecting, and the balance of it has been estimated by well-qualified men. This does not include a large area, and, consequently, tonnage on private lands which has not been visited and estimated by qualified men. Dr. Whitlatch is reluctant to place a figure on this unestimated tonnage, but hazards a guess that it will certainly amount to 20 million tons, and quite possibly to 40 million tons. I may add that Dr. Whitlatch is essentially conservative and at times even ultraconservative in his estimates.
>
> The effect of more efficient and new methods of concentrating and mining is illustrated by the fact that one operator stated that if he dropped his grade from 45 per cent to 35 per cent on one particular tract, it would increase his tonnage by over 50 per cent.
>
> No attempt has been made to estimate the blue rock reserves as it is not felt that there is any additional data to what Phalen used in his earlier estimate of 86 million tons.
>
> The white rock deposits are very largely a matter of guess work. My own guess (and it is distinctly a guess) is somewhere between 15 million and 20 million tons of 45 per cent, or higher grade. . . ."

The 86,000,000 tons of brown rock may safely be considered known reserves. To these may be added as probable reserves the 20,000,000 tons on private lands less well explored. The

total, or 106,000,000 tons of brown phosphate, is the same as that presented at the hearings. No figure for phosphatic limestone is included. This limestone needs further study as it may prove a very large, low grade resource, but data regarding its phosphate content are now apparently meager.

There seems no reason to change Jacob's revision of the Phalen estimate for blue rock. It has not been mined recently so the figure may stand at 83,233,000 tons.

Data for the white rock are meager. The lower figure given by Capt. Pond, 15,000,000 tons, may be accepted as representing possible reserves.

Revised figures for Tennessee are summarized as follows:

Brown rock	106,000,000 *
Blue rock	83,233,000
White rock	15,000,000
	204,233,000

* Whitlatch in paper presented before Am. Int. Min. and Met. Engrs., at Tuscaloosa, Ala. Nov. 3, 1939, and offered for publication by the Institute now gives brown rock reserves as 96,918,000 tons.

KENTUCKY FIELD.[19]

Deposits of brown phosphate similar in appearance and origin to those of Tennessee have been found in Fayette, Woodford, Scott, Jessamine, Franklin and Clark counties in central Kentucky and prior to 1927 some phosphate was produced near the town of Wallace in Woodford County. Jacob's figures, based on Phalen's and allowing for subsequent mining but not for flotation, give Kentucky 863,000 long tons.

ARKANSAS FIELD.[20]

The phosphate deposits of Arkansas are in the Cason shale of late Ordovician age and have been found in Stone, Izard, Searcy,

[19] Phalen, W. C.: The Central Kentucky phosphate field. Ky. Geol. Surv. in cooperation with the U. S. Geol. Surv., Frankfort, Ky., 1915.

[20] Branner, J. C.: The phosphate deposits of Arkansas: A. I. M. E. Trans., 26: 580–598, 1896.

Purdue, A. H.: Developed phosphate deposits of northern Arkansas. U. S. Geol. Surv. Bull. 315: 463–473, 1907.

Miser, H. D.: Deposits of manganese ore in the Batesville District, Ark. U. S. Geol. Surv. Bull. 734: 25, 26, 55, etc., map, 1922.

Marion, Baxter, Newton, and Independence counties in the northern part of the State. The phosphate occurs as an original sedimentary deposit analogous to the blue phosphate of Tennessee. On Lafferty Creek in northwest Independence County, about 12 miles northwest of Batesville, the section shows a low grade phosphate bed about 4 feet thick separated by a 2-inch bed of manganiferous iron ore from an overlying bed of higher grade phosphate 4½ to 6 feet thick. Here production was in progress between 1900 and 1912. The grade of the rock is lower than that of Tennessee but the deposits are favorably located with respect to possible markets west of the Mississippi River. Very likely the grade of the product could be improved by grinding and flotation or other means but I do not know of any such work having been done on Arkansas rock. Phalen's estimate of 20,000,000 tons has not been changed but it would not be surprising if detailed investigation might show the reserves to be much larger.

WESTERN FIELD.

The Western phosphate field covers parts of Utah, Idaho, Wyoming, and Montana and has extensions northward into Canada (Fig. 4).

Geologic Age.—The phosphate occurs in two geological formations, one of upper Mississippian age and the other Permian. Mississippian phosphate has been found chiefly in Utah but the horizon has been recognized here and there in Idaho. In general it is of low grade and not of commercial interest. The Permian phosphate comprises the major deposits of the Western field. In Idaho, Montana, and western Wyoming it is contained in the Phosphoria formation. Elsewhere in Wyoming it forms part of the Park City and Embar formations and in Utah it has hitherto been assigned to the Park City. Williams[21] now proposes to extend the use of the term Phosphoria from Idaho into Utah.

Mode of Occurrence.—The phosphate lies in regular beds like sandstone or shale and is of marine origin. Together with ac-

[21] Williams, J. Stewart: "Park City" beds on the southwest flank of Uinta Mountains, Utah. A. A. P. G., Bull. 23, no. 1: 82–100, 1939.

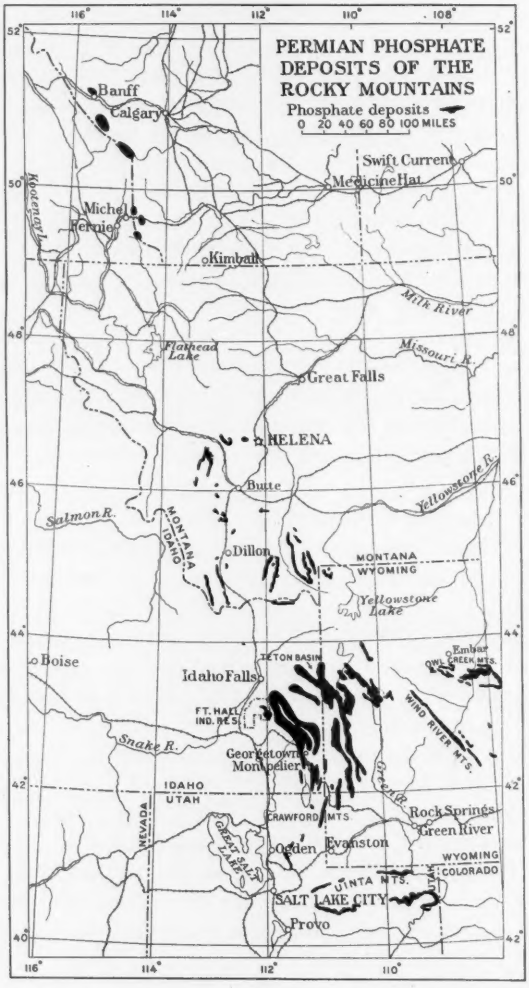


FIG. 4. Map of the Permian phosphate deposits of the Rocky Mountains.

companying formations it has been folded, faulted, and eroded so that it outcrops in bands that extend across country for many miles and the beds stand at any angle between horizontal and vertical. In places they have even been overturned. Accordingly, the phosphate must be mined by underground methods like coal.

Stratigraphic Character and Relations.—The phosphate is contained in the phosphate shale member of the Phosphoria formation or in comparable position in the other formations named. In Idaho it is overlain by massive and thinbedded chert, which makes striking topographic features, easily recognized, and is underlain by ledge-making siliceous limestones of Pennsylvanian age, also prominent topographically. The phosphate shale member itself from 75 to 175 feet or more thick contains beds of shale, sandstone, and limestone as well as beds of phosphate rock. Generally there is a "main bed" of phosphate 5 or 6 feet thick and of good quality near the base, and another similar but thinner bed near the top. In between are other beds differing in number, thickness, and quality at different localities. One of the best sections seen is that in Georgetown Canyon.[22] The main bed here, 6 feet 4 inches thick, contains 80.4 per cent of B. P. L. In the middle of the section are three beds that together comprise about 11 feet of phosphate containing more than 70 per cent of B. P. L. and there are in addition 8 other beds 5–17 feet thick containing 25–56 per cent of B. P. L. Some of the phosphate is thinbedded and friable and breaks down readily into loose earth but retains its characteristic oolitic texture. The oolites are small, rounded grains ranging in size from little larger than pin points to more than 1/16 inch. Other beds ranging in thickness up to 6 inches or more are relatively harder and break up into blocks or lumps. The oolites commonly show a concentric structure and in some beds larger grains or nodules have been formed by successive coatings of phosphate on fish teeth or mineral grains. In some beds no concentric structure is seen in the oolites and the phos-

[22] Richards, R. W., and Mansfield, G. R.: Geology of the phosphate deposits northeast of Georgetown, Idaho. U. S. Geol. Surv. Bull. 577: 24–25, 1914.

phatic grains are closely pressed together. Here and there beds are composed of phosphatized shell fragments.

Prospecting.—Prospecting in the Western field does not ordinarily involve boring but is done by digging pits or trenches on the surface or by driving tunnels and drifts. When a good bed is exposed, a face is cleaned off and sampled by channelling in the same way as a bed of coal. Such prospecting and sampling as the Geological Survey has done has been in connection with the classification of the public lands and not with the primary object of blocking out reserves. Hence the prospects have not been systematically spaced and are much farther apart—in some regions several miles—than they would be if the development of reserves had been the primary objective.

Mining and Beneficiation.—The mining of phosphate involves no special or unusual features although difficulties and expense have been encountered in some places where unfavorable ground had to be penetrated. No expensive washing equipment, such as must be used in Florida or Tennessee is required. This tends to offset the higher cost of mining. The rock as taken from the mine is simply crushed and dried to remove moisture or it may be calcined to remove CO_2 and organic matter.

Phosphate Land Classification.—On December 9, 1908, the Secretary of the Interior withdrew from all kinds of entry 4,541,300 acres of public land in Idaho, Utah, and Wyoming, pending their classification as phosphate or non-phosphate land. The Geological Survey began the work of classification the following season, 1909, and has continued it intermittently until the present, two projects, one in Idaho and one in Wyoming, being still in progress. As work continued some lands were restored as non-phosphate, others classified and restored as phosphate and still others withdrawn pending classification. Progress in the work is indicated by the fact that some 302,099 acres have been classified as phosphate land. Of this acreage Idaho has 270,036; Montana, 3,833; Utah, 2,937; and Wyoming, 25,293. Similarly a large acreage has been classified as non-phosphate and restored for entry. The outstanding withdrawals as of July 31, 1939, include 1,822,805

acres of which 276,239 are in Idaho, 280,089 in Montana, 277,344 in Utah, and 989,133 in Wyoming.

The data used for classification are the detailed areal geologic

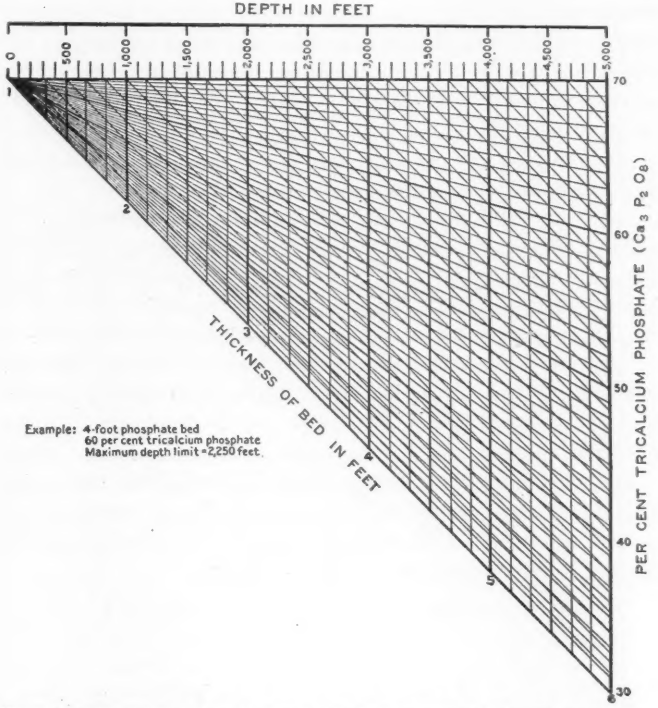


FIGURE 26.—Diagram illustrating the graphic method for determining the depth at which phosphate may be reserved in public lands. (From U. S. Geol. Survey Bull. 537, 1913)

FIG. 5. Diagram illustrating the graphic method for determining the depth at which phosphate may be reserved in public lands. (From U. S. Geol. Survey Bull. 537, 1913.)

maps and geologic structure sections provided by the geologist together with such other information as he has been able to obtain by prospecting and sampling. The depth limit for classification of

beds of different thickness and phosphate content is obtained by applying certain principles and regulations devised in the Survey offices.[23] See Fig. 5.

Reserves.—As the main phosphate bed in the Western field has hitherto been considered as the one most likely to be mined, all figures relating to reserves have been based upon showings obtained from that bed. Thus, much good phosphate has undoubtedly been ignored in preparing estimates. On the other hand if too great depths have been assumed, or if losses are encountered through former crustal movements, the ignored phosphate would seem to provide an ample margin of safety.

Now that flotation, electric furnace, and other methods of recovery are being applied to phosphate rock it may be possible to change future mining methods so as to include greater thicknesses of the phosphate shale and to justify deeper operations than those feasible for a 6 or 8-foot bed. Such considerations also serve to increase the hitherto published estimates of reserves, although from present data such an increase could not be made very specific. Probably it would be safe to assume that these figures could be doubled or perhaps trebled without undue violence to facts. However, I am not prepared now to make this expansion and prefer to give the figures on the old basis with such corrections as can be applied to bring them up to date. On this basis the figures for the four Western States are given as follows:

RESERVES OF PHOSPHATE, WESTERN STATES AS OF SEPTEMBER 2, 1939.

Idaho	5,736,335,000	tons
Montana	391,323,000	"
Utah	326,745,000	"
Wyoming	115,754,000	"
	6,570,157,000	"

Additional work done by the Geological Survey, or in progress by members of its staff will increase significantly the figures for Idaho and Wyoming. Dr. J. Stewart Williams[24] of the Utah

[23] Smith, G. O. and others: Classification of the public lands. U. S. Geol. Surv. Bull. 537: 131, 1913.

[24] Williams, J. Stewart: Phosphate in Utah. Utah Agr. Exp. Sta. Bull. 290, Aug. 1939.

State Agricultural College has recently made an independent study of the phosphate resources of Utah, including areas not studied in detail by the Geological Survey. His results show a greatly increased reserve tonnage for Utah. Estimating reserves in 7 counties and including material ranging down to 40 per cent in B. P. L. content he figures a total of 1,741,480,000 tons.

SUMMARY OF PHOSPHATE RESERVES OF THE UNITED STATES.

In connection with the activities of the Congressional Committee to Investigate the Adequacy and Use of Phosphate Resources of the United States new evidence brought out at the hearings showed that the phosphate resources of the United States are far greater than previously supposed, amounting at present reckoning to more than 10 billion tons not counting those reserves classed as possible or the phosphatic limestones of Florida and Tennessee. As more than 66,000 acres of withdrawn land in the Florida field and nearly 2,000,000 acres of withdrawn land in the Western phosphate field remain to be examined, and as the present estimates for the Western field apply only to the main bed and thus ignore much phosphate that may ultimately become available, it seems clear that figures for reserves may be enlarged still further. At the present rate of consumption, 3,000,000 tons annually, 10,000,000,000 tons would last more than 3,000 years.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
November 13, 1939.

USE OF SEDIMENTATION FEATURES AND CLEAVAGE IN THE RECOGNITION OF OVERTURNED STRATA.[1]

PHILIP J. SHENON AND ROGER H. McCONNEL.

ABSTRACT.

In mapping the closely folded Belt sediments of the Coeur d'Alene district, Idaho, the question frequently arises whether certain beds are overturned or not. The answer can in many cases be found by observing mud cracks, ripple marks, cross-bedding, and vertical gradations of grain size. Even more helpful is cleavage, which is developed throughout the district and therefore can be used in many places where the sedimentation features just enumerated are lacking. The cleavage is believed by the writers to be mainly fracture cleavage. Both flow and fracture cleavage are useful in detecting overturns, because both dip more steeply than the beds in the upright limb and less steeply than the beds in the overturned limb of an overturned fold. Drag in cleavage, as in bedding, may indicate the proximity of faults. All these relations of cleavage to other structures are well illustrated in the Big Creek anticline.

INTRODUCTION.

FIELD work in the Silver Belt of the Coeur d'Alene mining district, Idaho, was carried on during 1936–1937 under a cooperative agreement between the United States Geological Survey and the Idaho Bureau of Mines and Geology. Certain sedimentary and structural features in the Belt series of pre-Cambrian rocks were consistently used in working out the structures that influenced deposition of ore bodies. Mud cracks, ripple marks, cross-bedding, gradation in grain size from the bottom to the top of a bed, and pit and mound structure are the sedimentary features used; cleavage is the structural feature.

These features have long been recognized and some of them were effectively used in the Coeur d'Alene district by Calkins[2]

[1] Published by permission of the Director of the United States Geological Survey.

[2] Ransome, F. L., and Calkins, F. C.: Geology and ore deposits of the Coeur d'Alene district, Idaho. U. S. Geol. Surv. Prof. Pap. 62: 42, 61, 1908.

as early as 1905, yet it is considered worth while to emphasize their value when applied to the working out of structures in a closely folded region. The chief use of these features is in the recognition of the tops of beds and consequently of overturns, which is of economic importance in the Coeur d'Alene district because the productive veins, for example, those of the Sunshine and Polaris mines, are in the overturned limb of the asymmetrical Big Creek anticline [3] (Figs. 1 and 2).

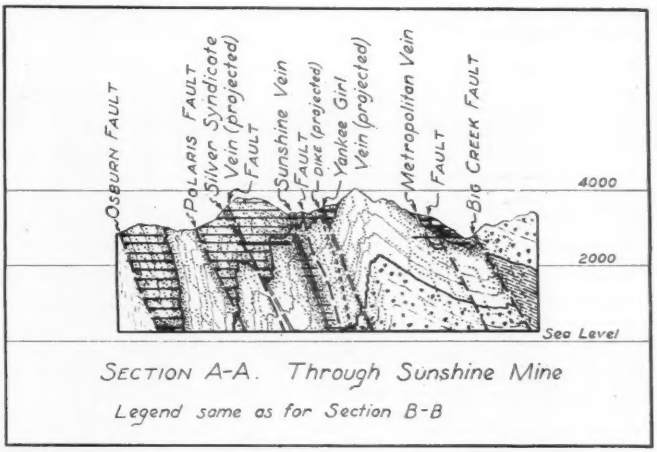


FIG. 1. Section through the Sunshine mine, showing the relation of the Sunshine vein to be overturned limb of the asymmetrical Big Creek Anticline.

CHARACTER OF THE BELT SERIES.

Except for lamprophyre and diabase dikes, the Belt series comprises the only consolidated rocks exposed in the Silver Belt. This series consists principally of quartzite, argillite, slate and calcareous rocks, which in the aggregate have a minimum thickness that probably exceeds 20,000 feet. Calkins [4] divided the Belt

[3] Shenon, P. J., and McConnel: The silver belt of the Coeur d'Alene district, Idaho. Idaho Bur. Mines and Geol. Pamphlet 50, 1939.

[4] Ransome, F. L., and Calkins, F. C.: Op. cit., p. 23, 1908.

series into six formations which he named in ascending order Prichard, Burke, Revett, St. Regis, Wallace, and Striped Peak. The Prichard formation is chiefly laminated black argillite and light gray, slightly sandy argillite. It contains two well-defined horizons of massive, white and gray quartzite. The Burke for-

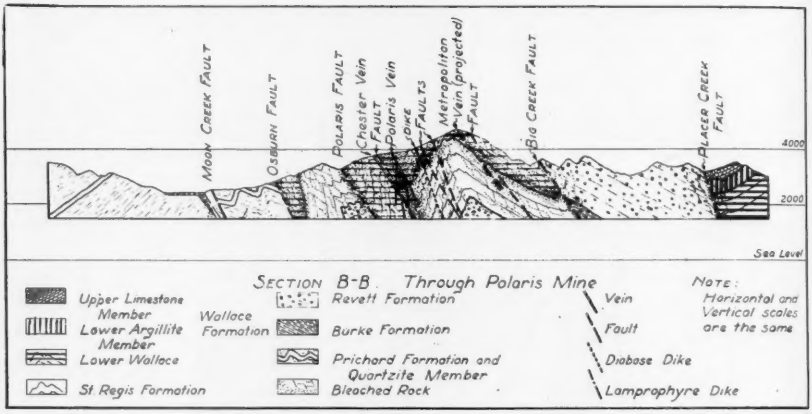


FIG. 2. Section through the "Silver Belt" of the Coeur d'Alene mining district, showing the position of the Polaris and Chester veins in the asymmetrical Big Creek Anticline.

mation consists of gray and greenish-gray sandy argillite, gray and nearly white massive quartzite, and some calcareous quartzite. The Revett consists of thick, massive beds of white and light gray quartzite, and a little gray sandy argillite and calcareous quartzite. Thin-bedded purple argillite alternating with subordinate amounts of pink quartzite, limy gray quartzite, and, near the base, massive white quartzite constitute the St. Regis formation. The Wallace formation is a series of thin alternating beds of black argillite, nearly white quartzite, limy quartzite, and considerable laminated black and light gray argillite. The Striped Peak formation is similar in constitution to the St. Regis formation.

SEDIMENTATION FEATURES.

Mud Cracks.—Mud cracks are common throughout the Belt series, but they are best displayed in formations with alternating beds of contrasting colors. They are especially well shown in the alternating black argillite and gray, more or less limy quartzite of the Wallace formation. Some are also found in the St. Regis, Striped Peak, and Burke formations, but very few appear in the massive quartzites of the Revett formation. Only a few were noted in the Prichard formation.

Mud cracks are most useful for determining the tops of beds when seen in cross section, as in mine workings or on joint planes. Fig. 3 shows cracks in black argillite filled with the white sand of the overlying bed. They are widest at the top, where they merge into the bed above, and become narrower downward. They range in depth from a mere roughness on the top of an argillite bed to three inches.

The surface of a sun-cracked bed is a mosaic of more or less regular polygons separated by cracks that may be filled with the sediment of the overlying bed. According to Pirsson and Schuchert,[5] "After the whole series of mud-cracked deposits has become hardened into rock, the layers of shale and sand-stone may later be exposed, exhibiting these "fossil" mud cracks on the bedding planes. When the beds are thus exposed, the softer, mud-cracked layers commonly crumble away, leaving natural casts of the mud cracks as projecting ridges on the lower surfaces of the sandstone layers."

Though the writers observed such "natural casts" of mud cracks on the surfaces of many beds, they do not consider them as reliable criteria for determining the upper side of beds. It was many times noted that the filling of the mud cracks projected outward from the weathered top of the mud-cracked layer rather than outward from the bottom of the filling layer (Fig. 4). In many exposures also, mud cracks are represented by depressions between the mud-polygons, indicating that the filling material was

[5] Pirsson, L. V., and Schuchert, Charles: A Textbook of Geology, 3d ed., p. 225, New York, John Wiley & Sons, Inc., 1929.

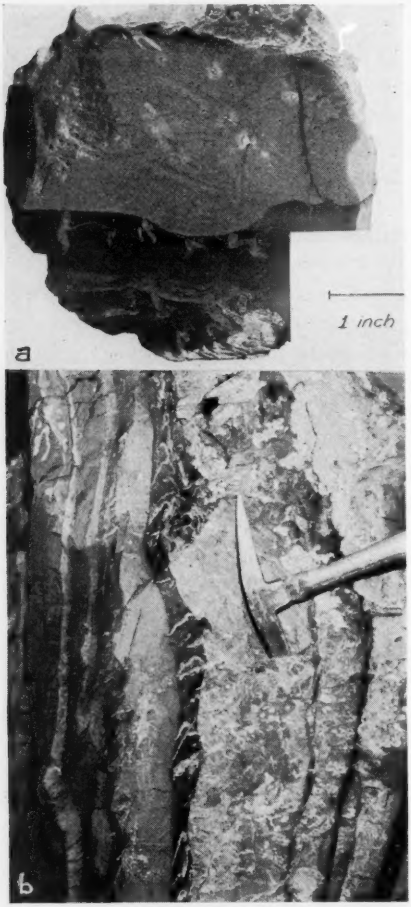


FIG. 3. *a*, Mud cracks in black argillite of the Wallace formation filled with white quartzite (light gray) of overlying bed.

b, cross section of filled mud cracks in vertical beds of Wallace formation whose tops face right.

less resistant to erosion than the material that cracked while drying.

Ripple Marks.—Both wave, or oscillation, ripple marks, and current ripple marks are abundant in the sandy beds of the Belt

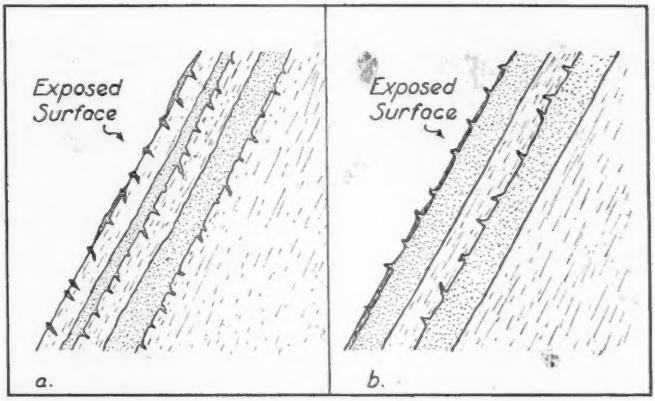


FIG. 4. (*a*) Sketch showing upright beds of mud-cracked argillite filled with overlying sandstone, which being resistant to erosion projects outward from the top of the argillite bed.

(*b*) Overturned beds in which the resistant fillings of the mud cracks project outward from the bottom of the sandstone beds, and represent the bottoms, rather than the tops, of the fillings. Thus, mud crack fillings projecting from a bedding surface may represent either the top or the bottom of the mud crack, and are therefore not reliable in plan view for determining the upper side of the bedding surface.

series. The agitation resulting from the oscillatory movement of water produced by wave action throws the granular sediment into ripple ridges that coincide in direction with the trend of the waves.[6] Ripple marks thus produced are characterized by symmetrical, sharp-crested ridges alternating with wide troughs and are therefore useful for identifying the top side of beds (Fig. 5).

Current ripple marks are asymmetrical (Fig. 6), with their

[6] Twenhofel, W. H., and others: Treatise on Sedimentation, 2d ed., p. 650, 1932.

gentle slopes facing upstream. They have little value for deciphering structure because they look the same whether viewed from top or bottom. All the current ripples seen were small, none having a wave length over 6 inches, nor an amplitude greater than 1½ inches. The ripple index, that is, the ratio of amplitude

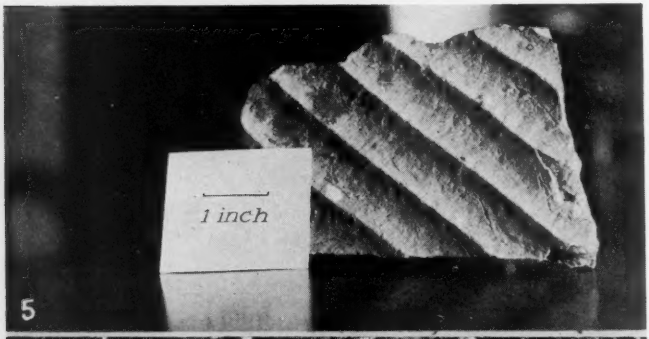


FIG. 5. Wave, or oscillation ripple marks from the Striped Peak formation. Note the sharp crests and broad, symmetrical troughs.

FIG. 6. Current ripple marks from the Striped Peak formation. The longer, gentler slopes face upcurrent.

[7] Twenhofel, W. H., and others: Op. cit., p. 666.

to wave length, is about 1 to 7, which is characteristic of water-formed ripples.[7]

In addition to the simple current and wave ripple marks numerous complex forms are abundant in the Belt sediments. There are many examples of compound current ripple marks resulting from the modification of a pre-existing set of current ripple marks by a later cross-current. "Tadpole nests," or interference wave ripple marks, also occur. These forms are caused by an abrupt change of wind direction, which superimposes a crossing set of wave ripple marks over the earlier-formed set, thus forming a mosaic of polygonal pits separated by intersecting, sharp crests.

Numerous casual references classify ripple marks as shallow-water features; but they are not formed in shallow water only. Current ripple marks may form in any depth of water at which the current is strong enough to move sandy or silty sediment. Hjort[8] has reported currents capable of moving sand, and therefore of producing ripple marks, at depths of 800 meters. Wave-formed ripple marks apparently are restricted to somewhat shallower depths, although oscillations capable of rippling bottom sediments have been noted at depths up to 80 fathoms.[9]

Cross-Bedding.—Cross-bedding, or false bedding, consists of sub-parallel sandy layers lying at angles to the general stratification. At the base of a bed the laminæ approach parallelism to the stratification planes, whereas at the top the laminae are sharply truncated by the overlying stratum thus giving a reliable means for recognizing the tops of beds (Fig. 7).

Cross-bedding is present in many of the quartzitic rocks of the Belt series and is particularly useful for interpreting the structures in the massive quartzite beds of the Revett and Burke formations. Because of the etching out of carbonate grains, cross-bedding is especially conspicuous in weathered exposures of the calcareous beds of these formations.

[8] Hjort, J.: The "Michael Sars" North Atlantic deep-sea expedition. Geog. Jour., 37: 349–377, in Twenhofel, W. H.: Op. cit., p. 660.

[9] Twenhofel, W. H.: Op. cit., p. 661.

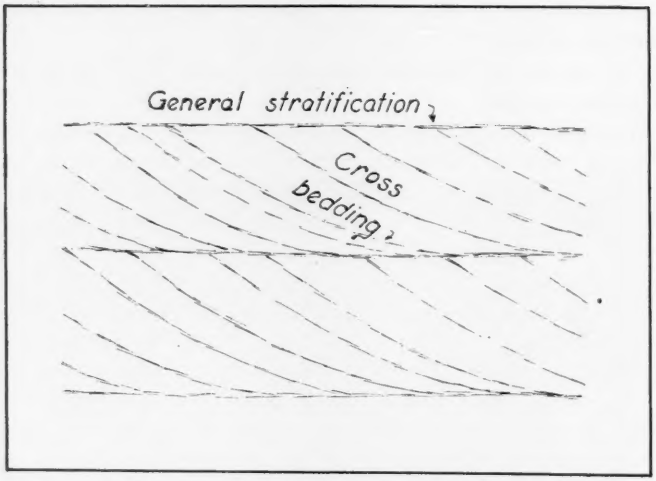


FIG. 7. Sketch of cross-bedding, illustrating the truncation of the tops of the cross laminae by the upper surface of general stratification.

Gradation in Grain Size.—Gradation in grain size, especially where it is accompanied by a color change, is a sedimentary feature that is of considerable use in working out structures. The gradation is usually discernable as a gradual change from light-colored quarzite in the lower part of a layer to dark-colored argillite in the upper. At the top, the dark-colored argillite is abruptly succeeded by the overlying layer of light-colored quartzite.

Gradations of this sort are frequently seen in the Wallace formation, where the strong contrast between the dark argillite and white quartzite makes them strikingly conspicuous; they occur, but are less conspicuous, in the St. Regis and Prichard. In some of the Prichard beds, the alternating black and white laminae are so thin that gradations cannot be recognized in hand specimens, but thin sections cut at right angles to the bedding often show enough gradation in grain size to determine which were originally the upper sides of the laminæ.

Pit and Mound Structures.—The bottoms of some of the light

gray and more quartzitic laminæ of the Prichard formation are marked by sharply defined, crinkled surfaces, whereas the tops of these laminæ join smoothly with the overlying black laminæ

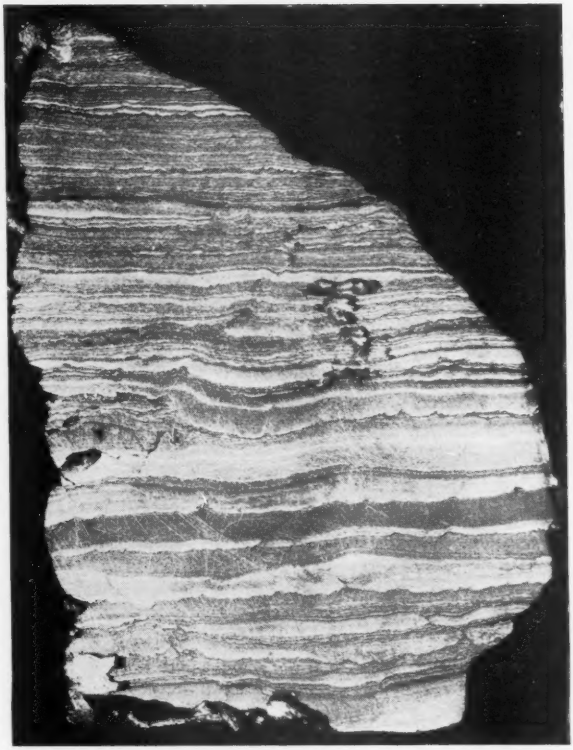


FIG. 8. Cross-sectional view of a hand specimen of Prichard argillite. The bottom edges of the white, slightly sandy laminae are commonly crinkled, whereas the top edges are straight.

(Fig. 8). Careful checking against evidence presented by mud cracks, cross-bedding and cleavage demonstrates that the crinkled surfaces are always at the base of the gray quartzitic layers.

The origin of this crinkly surface is obscure, but in plan it resembles the pit and mound structures described by Twenhofel.[10]

CLEAVAGE.

Cleavage is more generally useful as a means of recognizing overturned beds than the sedimentation features discussed above, because it is present throughout the Belt sediments of the Coeur d'Alene district and can be used in many localities where ripple marks, mud cracks and cross-bedding are lacking. It is particularly useful for identifying the tops of beds in mine workings.

As defined by Leith,[11] fracture cleavage is

> a capacity to part along closely spaced parallel surfaces of fracture or near-fracture, commonly in a single set, but occasionally in intersecting sets. Fracture cleavage differs from ordinary flow cleavage or schistosity in that the surfaces of breaking are not determined by a parallel arrangement of mineral particles, but are independent of any such arrangement. Also it does not pervade the entire mass and affect all particles as does flow cleavage.

Both fracture cleavage and flow cleavage are probably present in the Coeur d'Alene district, although the distinction between them is not clear in many places. For example, cleavage in the more argillaceous rocks may more nearly fit Leith's definition of flow cleavage, whereas in nearby quartzitic rocks it corresponds with his definition of fracture cleavage. Calkins[12] considered that the cleavage in the Coeur d'Alene district corresponded with flow cleavage as defined by Leith whereas the writers of this paper believe that most of the cleavage exposed in the Silver Belt more nearly corresponds with Leith's definition of fracture cleavage, and that most of the sericite mica along the cleavage in the Silver Belt has been formed by hydrothermal alteration after the cleavage was developed.

Leith[13] points out that flow cleavage is parallel, and fracture cleavage is nearly parallel, to the axial plane of the fold in which each is developed. To this theorem he has added the following corollaries, which apply to both fracture and flow cleavage:

[10] Twenhofel, W. H.: Op. cit., pp. 680–682.

[11] Leith, C. K.: Structural Geology, rev. ed., pp. 148–149, 1923.

[12] Ransome, F. L., and Calkins, F. C.: Opt. cit., p. 65.

[13] Leith, C. K.: Op. cit., p. 185.

1. That the trace of bedding on a cleavage plane gives the angle of pitch of the fold.[14]

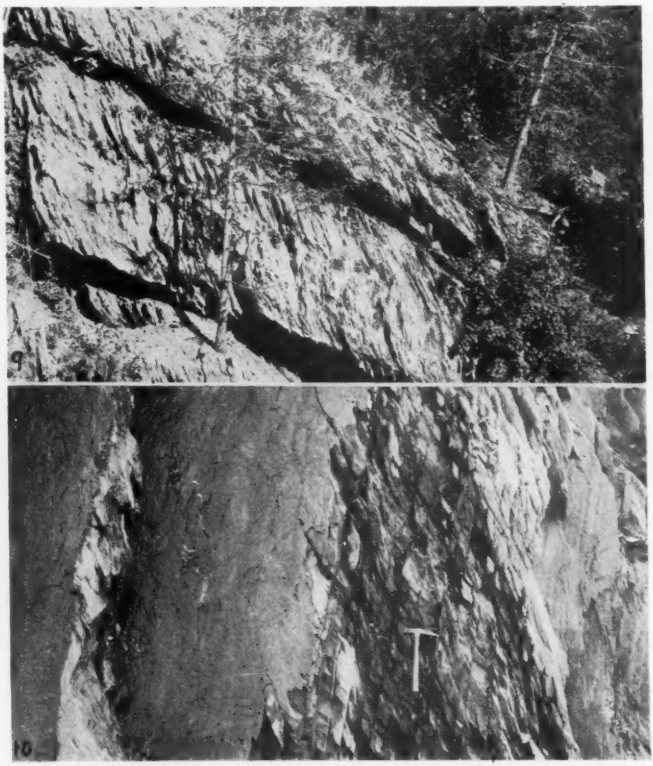


FIG. 9. Cleavage in beds of the St. Regis formation, shown by the light, closely spaced, vertical shadows. Bedding is parallel to the two dark shadows, dipping to the right. The beds are right side up.

FIG. 10. Cleavage in steeply dipping beds of the St. Regis formation. Bedding dips about 80° left, and cleavage about 60° right. The tops of the beds face left.

[14] Leith, C. K.: Op. cit., p. 185.

2. That an observer's position in relation to the axial plane of a fold may be determined by the relation of cleavage to bedding.[15]

3. That the top side of beds is shown by the attitude of cleavage relative to bedding.[16] If cleavage dips at a steeper angle and in the same direction as bedding, the beds are right side up (Fig. 9). Conversely, if cleavage dips at a lesser angle and in the same direction as bedding, the beds are overturned (Fig. 12). If cleavage and bedding dip in opposite directions, the top side of the bed faces upward (Figs. 10 and 11).

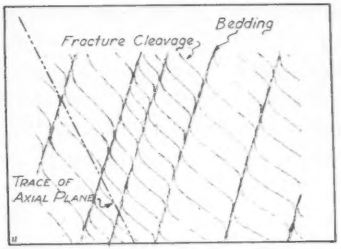
Although these corollaries and their basic theorem are strictly applicable only to incompetent beds,[17] it should be pointed out that even in quartzite bands, fracture cleavage may be useful for determining the tops of beds, in spite of the fact that the cleavage may not be parallel with the axial plane of the fold. Moreover, in many quartzite beds, fracture cleavage has greater usefulness because its trace on a vertical plane has a pronounced "S" shape, toward either end of which its attitude is approximately parallel to the axial plane of the fold (Figs. 11 and 12). The top of the "S" always points toward the axial plane of the anticline. This turning of fracture cleavage from its attitude in the middle of a bed to a position nearly parallel to the argillaceous parting at the bedding plane is the result of slight differences in grain size and therefore in relative competency and response to stress between the quartzite in the middle and outer parts of a bed. "S"-shaped cleavage is not seen in massive quartzite beds which do not have somewhat finer-grained material near the bedding surfaces.

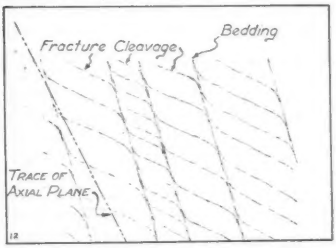
According to the strain theory, the bisectrix of the obtuse angle between bedding and fracture cleavage is the direction of non-rotational stress, and is normal to the axial plane of the fold (Fig. 13). To fulfil these conditions, fracture cleavage in an asymmetrical fold must have lower dips in the overturned limb than in the upright limb (Fig. 13).

[15] Leith, C. K.: Op. cit., p. 182.

[16] Leith, C. K.: Op. cit., p. 183.

[17] Swanson, C. O.: Notes on stress, strain, and joints: Jour. Geol., 35: 193–223, 1927.





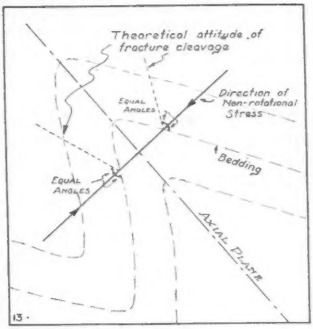


FIG. 11. Quartzite beds, not overturned, showing the "S"-shape of cleavage. Both ends of the "S" approximately parallel the axial plane of the fold. Tops of beds face left.

FIG. 12. Overturned beds, showing "S"-shape of cleavage. Tops of beds face left.

FIG. 13. Sketch illustrating the application of the strain theory to an overturned fold. Note that fracture cleavage is less steep on the overturned limb than on the upright limb.

This condition is fulfilled by cleavage in the eastward-trending asymmetrical Big Creek Anticline. In the overturned north limb of this fold, where the dip of the bedding ranges from vertical to 30° south, the cleavage dips from 70° to 15° south, being flattest in the beds which have the lowest reverse dips. In the upright south limb, in which the beds dip 30° to 45° south, the dip of the cleavage ranges from 60° south to vertical.

Anomalous dips of cleavage are found in and near the major fault zones, which are later than the folding. For example, cleavage commonly has an abnormally steep dip near the Polaris normal fault zone, which cuts through the overturned limb of the Big Creek Anticline. At some places in the Polaris fault zone the cleavage and bedding are intensely buckled and broken.

ACKNOWLEDGMENTS.

The writers wish to express their appreciation to F. C. Calkins, Charles Park, Jr., and E. C. Eckel of the U. S. Geological Survey for editorial help and numerous suggestions.

EXPLORATION GEOLOGIST,
INTERNATIONAL NICKEL CO.,
SUDBURY, ONT.
RESIDENT GEOLOGIST,
BUNKER HILL & SULLIVAN MIN. & MILL. CO.,
KELLOGG, IDAHO.

OPENINGS DUE TO MOVEMENT ALONG A CURVED OR IRREGULAR FAULT PLANE.[1]

W. H. NEWHOUSE.

ABSTRACT.

A method is described for making a three dimensional analysis of the curvature or irregularity of a fault. This analysis may be used to determine the position of the openings or zones of low compression that are formed when fault movement takes place. Use is made of two coördinate directions lying within the plane of the fault, one parallel to the direction of fault movement, the other perpendicular to it. The angular variations of fault irregularity parallel to each of these directions, and also perpendicular to them give an analysis that considers all three dimensions of space. These angular variations may be conveniently shown by contours.

The principles are briefly illustrated with dip-slip faults, and very briefly with strike-slip faults. The line of dip and line of strike of these faults approximate the two significant coördinate directions. Extension of the principles is left to the reader.

Two occurrences of ore deposits in dip-slip faults are briefly analyzed.

It has long been recognized that in the filled-fissure type of vein the thicker parts of the veins may occupy openings formed by movement along an irregular fault surface so that badly fitting portions are brought together leaving openings, as channelways for solutions, or for mineral deposition.

To form these faults the rocks broke along a curved or irregular fracture and were displaced. A feature of interest is the relation in a given fault vein between (1) amount of movement of the two opposing sides of this irregular surface and, (2) length parallel to the direction of fault movement of the curve or "opening" occupied by the ore shoot or shoots. For example, compare the amount of displacement in Fig. 1*a*, section x″-z″, with length of the opening.

[1] Part of a chapter by the writer in a symposium on Relations of Ore Deposits to Structural Features. The Symposium is being sponsored by the Committee on Processes of Ore Deposition, National Research Council. The writer is responsible for the opinions expressed in this paper.

In the forthcoming symposium on Relations of Ore Deposits to Structural Features a considerable number of ore deposits are shown to be in faults of several hundred feet or more displacement. Although fairly numerous, these appear to form only a small percentage of the total number. Many contributors to that volume have emphasized the relatively slight displacement along most of the faults in which ore bodies are found. The displacement is generally measured in tens of feet or less and becomes a subject receiving special comment when proven to be more than a few hundred feet.

Contrasted with these figures, the relatively open parts, or curves occupied by one or several ore shoots of mine size are usually to be measured in the plane of the vein in terms of hundreds rather than tens of feet. Without wishing to overemphasize the difference in magnitude of the two phenomena, it seems safe to assume that the ore shoots of sufficient size to make a mine, occupy "open" spaces or curves of a length along the vein that is generally greater than the total amount of fault displacement. If this is true, the walls of these ore shoots have moved enough during the faulting to throw them out of "fit" but not to an extent that would move one wall completely beyond its companion curve on the opposite wall (Fig. 1*a*).

The following geometric analysis of the curvature or irregularity of a fault shows favorable and unfavorable curvatures whether they are of this origin or are entirely accidental ill-fitting portions of fault walls.

FAULT DEVIATIONS OR CURVES THAT FORM OPENINGS AFTER FAULT MOVEMENT.

Von Cotta [2] recognized at an early date the relation between certain vein deviations, direction of fault movement and the position of related ore shoots. More recently Spurr,[3] Hulin [4] and

[2] von Cotta, B.: Die Lehre von den Erzlagerstattenlehre, 1859, p. 161.

[3] Spurr, J. E.: The Camp Bird compound veindike. ECON. GEOL., 20: 124, 1925.

[4] Hulin, C. D.: Structural control of ore deposition. ECON. GEOL., 24: 38–40, 1929.

others [5] have described or used certain of these deviations coupled with fault movement to explain the position of some ore deposits. The rules given are as follows: In normal faults a likely place for openings, and consequently ore shoots, is where the dip steepens; in reverse faults where the dip flattens. Similar principles obtain with strike deviations where an important component of the fault movement is parallel to the strike. Ferguson [6] in describing the Sixteen to One vein in the Alleghany District, California has mentioned a general relation between the dip and thickness of the quartz vein.

Although open spaces have long been recognized as solution channels or loci of ore deposition, only a part of the contributing geometric factors have been considered. It would seem desirable to consider all the geometric variants of any given area along a fault surface. In exploration for ore shoots along a vein it would be important to recognize variations, which if continued would be favorable for production of openings or, conversely, variations that would produce areas of compression, or support —resulting in a tight fault.

ANALYSIS OF THE DEVIATIONS OR CURVES OF A FAULT THAT PRODUCE OPENINGS AFTER FAULT MOVEMENT.

In the general case of a curved or irregular fault surface, let two lines at right angles to each other and lying within the surface of the fault represent coördinate directions. Let the angular variations of fault irregularity or curvature be measured in both parallel and transverse directions along each of these coördinates. This makes possible a three dimensional analysis of fault curvature or irregularity. The best coördinate directions to use are the line of fault slip and a line perpendicular to it and lying in the plane of the fault. The angular variations may be conveniently shown by contouring the surface of the fault.

[5] Anderson, Lovering and Wisser in the volume on Relations of Ore Deposits to Structural Features.

[6] Ferguson, H. G.: Gold-quartz veins of the Alleghany district, California. U. S. Geol. Surv. Prof. Pap. *172*: 108, 1932.

Two particular types of faults have been chosen for description and illustration:

I. Dip-slip faults, which include those of normal and reverse movement, and
II. Strike-slip faults.

These two types are regarded only as special cases of the general relationship, but have been selected because the angular changes along the fault with respect to direction of movement may be easily described by dip and strike. It hardly needs to be mentioned that the same geometric principles apply to those faults, along which the movement has been in a direction intermediate to dip-slip and strike-slip. The reader will find the following discussion more easily understood and visualized with the aid of strips of soft sheet copper bent to conform to each other and moved to represent the fault. Each of the two pieces may be cut almost completely through and then twisted to represent Figs. 1, *b*, *c*, and 4, *b*, *c*.

Variations of a curved fault surface along the two coördinate directions may be described as follows:

(*a*) Change of angle of dip along the line of dip
(*b*) Change of angle of dip along the line of strike
(*c*) Change of strike along the line of dip
(*d*) Change of strike along the line of strike.

With dip-slip fault movement three of these (*a*), (*b*) and (*c*) singly, or in combination all four, may participate in the formation of the curves or deviations that produce openings between fault walls. With strike-slip movement (*b*), (*c*) and (*d*) singly, or combinations of all four may participate. With movement between dip and strike slip all four may contribute to form the deflections.

The significant deviations are described and illustrated below:

I. Faults with Dip-Slip Movement.—In normal faults openings will tend to be formed and consequently ore shoots (*a*) where the dip steepens up or down the dip of the fault, (*b*) where the dip

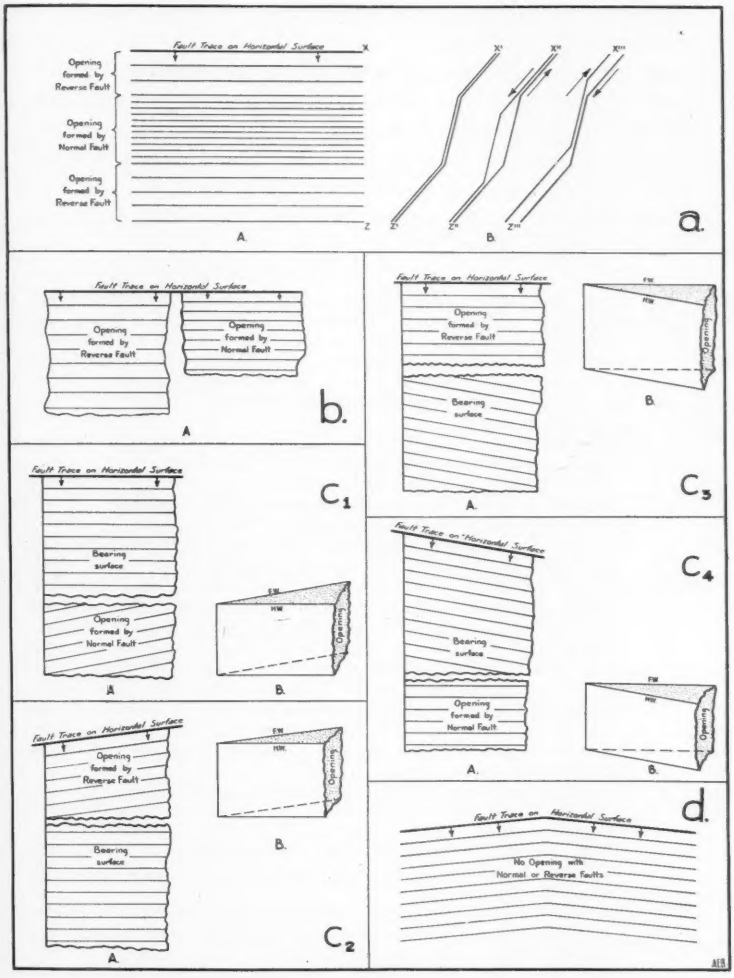


FIG. 1. Openings formed by fault curvature or irregularity along dip-slip faults. Effect of deviation along single coördinate directions.

A. Diagrammatic fracture surfaces dipping toward the reader and contoured before fault movement. Horizontal projection. The extent

steepens along the strike, (*c*) in relation to favorable changes in strike up or down the dip.

In reverse faults openings will tend to be formed and consequently ore shoots (*a*) where the dip flattens up or down the dip, (*b*) where the dip flattens along the strike, (*c*) in relation to favorable changes in strike up or down the dip. It should be noted that (*a*), (*b*) and (*c*) may each vary favorably so as to be supplementary to one another, or they may vary unfavorably to neutralize one another.

---

of openings shown in the diagrams *B* is dependent on curvature or irregularity, and amount of movement. In *b* and *c1, c2, c3, c4* two adjacent portions of a fracture surface are contoured and are connected by curvature or deviation of the intervening fracture surface. The connections have been omitted except for one line or trace in the present figures since they distract attention from the principle discussed.

a. Effect of change of angle of dip along the line of dip. x′z′ transverse vertical section of fracture before movement; x″z″ transverse vertical section after normal fault movement; x‴z‴ transverse vertical section after reverse fault movement.

b. Effect of change of angle of dip along the strike.

One portion of the contoured fracture surface dips steeply, the other less so. If the H. W. moves relatively down, it will ride on the flat dipping portion as a bearing surface, separating the H. W. from the F. W. on the steeply dipping portion to form an opening. Conversely, the steep-dipping portion becomes a supporting or abutment surface if the H. W. moves relatively upward, producing an opening along the flat-dipping portion.

c1–c4. Effect of change of strike along the line of dip. The angle of dip in the horizontally contoured portions of the surface is considered to approximate the apparent angle of dip along the continuous trace on the left side of the portion represented by the diagonal contour lines.

In *c1* and *c4* if the H. W. of the upper segment of the two contoured parts of the fracture moves down opposite the lower portion, an opening will be formed like *B* shown to the right.

In *c2* and *c3* if the H. W. of the lower segment of the fracture moves upward opposite the upper section, an opening like that in *B* will be formed.

These four examples *c1–4* illustrating the one principle are given for the reader's convenience in examining the combinations shown in Figs. 2 and 3, and in the Fanney Mine, Mogollon, N. M. and the Sixteen to One Mine, Alleghany District, California.

d. Effect of change of strike along the line of strike. No openings are formed by normal or reverse faulting where this factor alone is concerned. However, in combination, as with *e* in Fig. 2 it contributes to the formation of openings.

With dip-slip faults, change of strike along the line of strike (*d*) has no effect except in combination.

The illustrations of these single features (Fig. 1) have been made diagrammatic in order to show deviation along only one direction at a time. The openings with which ore shoots may be

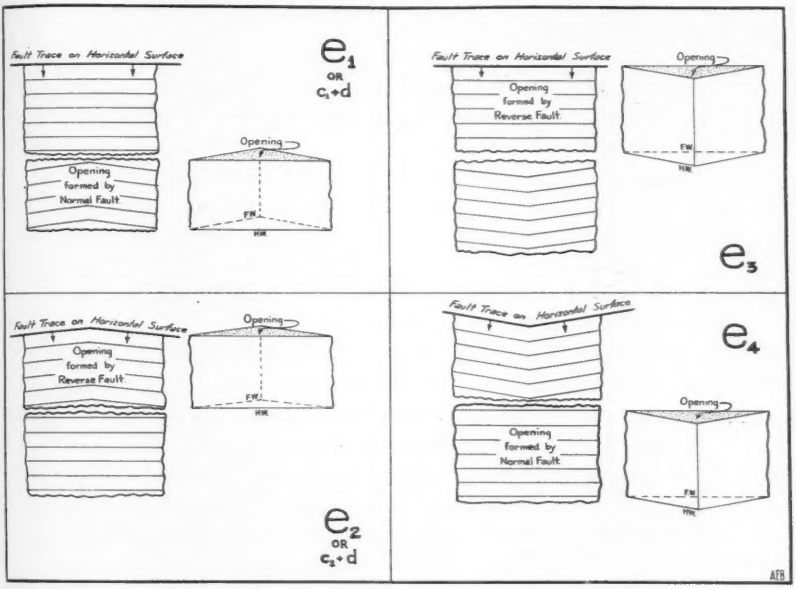


FIG. 2. Openings formed by fault curvature or irregularity along dip-slip faults. Effect of combination of 1*c* and 1*d*.

associated would probably seldom be formed by a curve or deviation along only one of these arbitrary directions.

In the figures, only general location and size of openings are indicated. The portions of the irregular fault walls that rub together and form bearing surfaces or the abutment areas are the parts that support the rocks, or take the pressure normal to the fault. During movement, other portions of the fault walls are pulled apart and arch or bridge across from one bearing area to

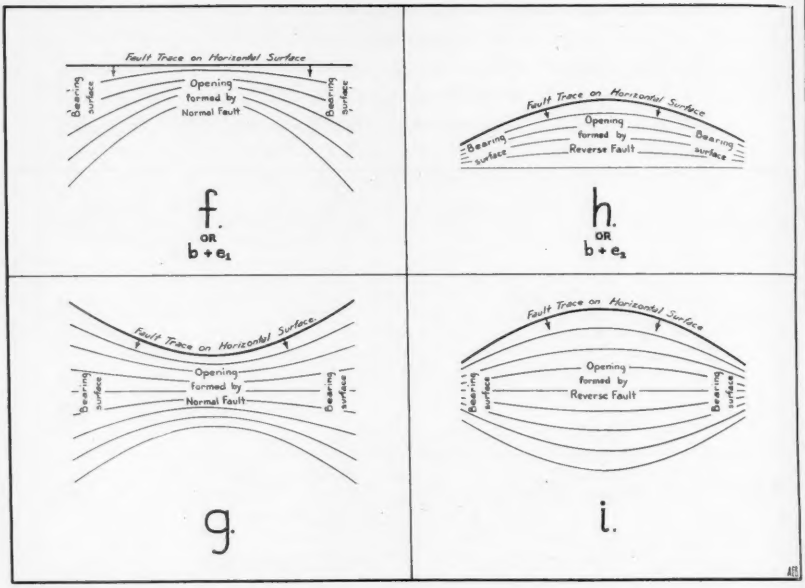


FIG. 3. Openings formed by fault curvature or irregularity along dip-slip faults. Effect of combinations of some deviations shown in Figs. 1 and 2. Diagrammatic fracture surfaces dipping toward the reader and contoured before fault movement. Horizontal projection. The relative size of opening and bearing surface formed by faulting is dependent on the curvature and amount of fault movement.

f. Combined effect of $b + e_1$.

It should be noted that the effect of *c* in examples where a gradual change of strike takes place along the line of dip may be to form openings in general *between* the extremes of favorable strike variation rather than on one of them as in *c*1–4. It should also be noted that the position of an "opening" with normal fault movement becomes a bearing zone or "tight fault" area with reverse fault movement.

g. Like *f*, but with a more accentuated tendency to form openings. If a fault surface is contoured by the Conolly method with reference to a plane approximately parallel to the fault surface and below or behind it "hills" and "depressions" appear. A portion of a fault with slight normal movement and a local curvature like that above the straight or median line of this diagram would appear as a "hill" and

another to form openings, or areas of low compression. Effective "bridging" or arching from two or three sides may be necessary to give a broad zone of ore shoots in "openings." The average example will probably be formed by components of two or three of the variations. Combinations that give pronounced "bridging" with faults of normal and reverse movement are shown in Fig. 3.

II. Faults with Strike-Slip Movement.—In faults where the displacement is chiefly horizontal, openings will tend to be produced: (*b*) where the dip flattens or steepens along the line of strike coupled with appropriate direction of movement, (*c*) in relation to favorable changes in strike along the line of dip with appropriate direction of movement, (*d*) where the strike changes along the line of strike coupled with the appropriate direction of movement.

The illustrations of fault deviations that are effective to produce openings where the fault movement is horizontal have been made to show pronounced "bridging" or support on only one side (Fig. 4). A pronounced curvature of the fault on one side of an "opening" such as is illustrated, for example, by Fig. 4*b* might taper off gradually on the opposite side of the "opening" and give space for solution movement and ore deposition. However, it seems likely that a more pronounced tendency to form openings would be where arching and support are present on more than one side. Study of these features connected with many ore shoots will eventually settle this question.

---

with local curvature like that below the median line a "depression."

h. Combined effect of $b + e2$.

i. Like *h* but with a more accentuated tendency to form openings. If a fault surface is contoured by the Conolly method "hills" and "depressions" appear. A portion of a reverse fault with slight movement and a local curvature like that above the straight or median line of this diagram would appear as a "depression" and with local curvature like that below the median line a "hill." These "depressions" and "hills" are thus genetically explained as caused by a combination of fault curvature and direction of fault movement.

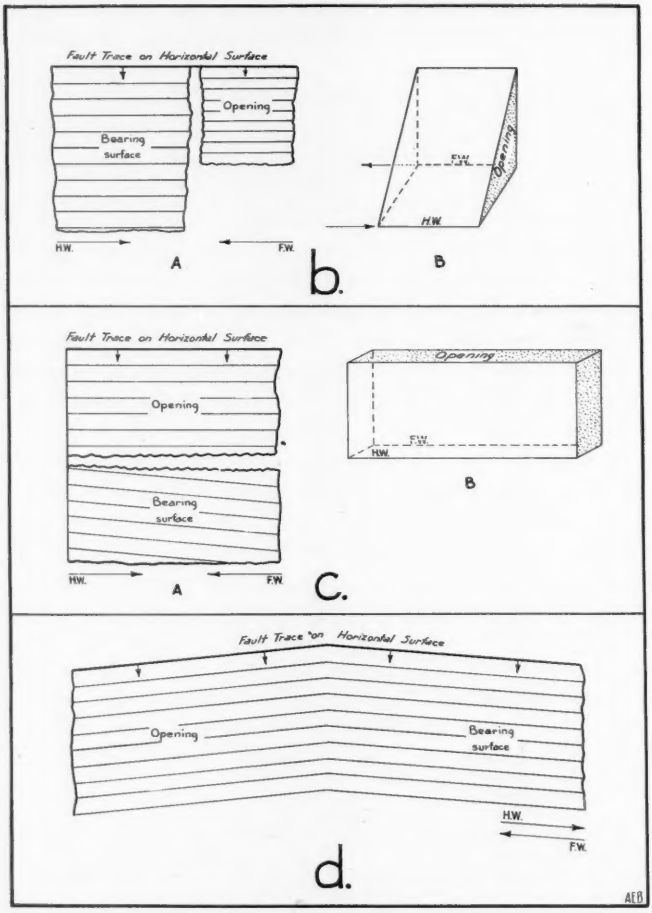


FIG. 4. Openings formed by fault curvature or irregularity along single coördinate directions of strike-slip faults.

A. Diagrammatic fracture surfaces dipping toward the reader and contoured before fault movement. Horizontal projection. The extent of openings is dependent on the curvature or irregularity of the fault and the amount of fault movement. In *A* of *b* and *c*, two adjacent portions of a fracture surface are contoured in each sketch.

EXAMPLES OF ORE SHOOTS RELATED IN POSITION TO CHANGES OF DIP AND STRIKE OF A VEIN.

Geometrical considerations suggest that the necessary deviations to give vein widths of several feet may not appear clearly on small scale maps. The ordinary mine level map, where drifting is done on the vein, at 100 foot levels is too small a scale to measure and study any but rather large deviations. The more accentuated curvature associated with some veins may appear on maps of a scale less than 100 feet to the inch. Where the fault vein does not dip too steeply, contours on the vein projected to a horizontal plane should show the curvature and relationships. With steeply dipping faults it may be necessary to tilt the usual horizontal plane of projection so as to spread the contours.[7] Where the fault has large components of both dip- and strike-slip movement the writer would prefer to contour the fault with reference to a plane, that is, oriented with respect to movement as is the horizontal plane to moderately dipping faults with dip-slip movement.

It should be emphasized that an "opening" along a fault or an ore shoot in a vein has three dimensions and, therefore, an analysis of fault irregularity that includes only two dimensions may

---

These portions of the fracture are connected by curvature or deviation of the intervening fracture surface. These connecting portions have been omitted except for one line or trace so that the attention may be centered on the principle discussed. Only one bearing surface to give bridging or arching is shown with each example.

b. Effect of change of angle of dip along the strike.

One portion of the contoured fracture dips steeply, the other portion has a smaller angle of dip. With movement of the H. W. as shown by the arrow, an opening is formed between the flat-dipping H. W. and the more steeply dipping footwall. (See *B*). In geometric principle this is like *c* in Fig. 1.

c. Effect of one change of strike along line of dip.

By reversing the direction of movement the other general case may be visualized. With a given amount of fault movement in the direction shown by the arrows, an opening will be formed like *B*. In geometric principle *4c* is like *b* in Fig. 1.

d. Effect of change of strike along the line of strike. In geometric principle *4d* is like *a* in Fig. 1.

[7] See also Conolly, H. J. C.: A contour method of revealing some ore structures. ECON. GEOL., 31: 259–271, 1936.

give erroneous results. A common error is to consider only one of the angular variations along one or both of the coördinate directions. The coördinate direction and angular variation likely to be neglected are those perpendicular to the direction of fault movement. Thus, with a dip-slip fault the variations in fault dip may be considered, but the equally significant variations of the fault strike may receive no attention. Although very pronounced change along one angular deviation of one coördinate may form an "opening" it is certain that the contour pattern of a fault should be considered as a whole in making a final analysis.

ORE DEPOSIT IN A NORMAL FAULT.

Ore deposition in the anticipated position of openings along a vein is afforded by the Little Fanney mine, one of the largest producers of gold and silver in the Mogollon District, New Mexico. The ore shoots in this district are in veins filling faults that cut a thick series of volcanic rocks of andesitic and rhyolitic composition. The mineralization is epithermal and the ore shoots are said to be confined to a fairly well defined zone that is less than 1000 feet thick.[8] At the Little Fanney mine the ore is in a normal fault with an apparent vertical displacement of about 300 feet.[9] According to Ferguson, the workings on this vein cover a vertical range of 1500 feet and a length of 4000 feet on the strike of the vein. Ore had been exposed, at the time of the report, through a vertical distance of 1200 feet to the 1100-foot level and for about 2700 feet along the strike. The strike over the greater part of the vein is N. 74° W. and the dip about 70° S. (Figs. 5, 6). In the western part of the workings the vein appears to split into several branches. Minor splits in the vein are numerous and according to Ferguson appear to exercise some degree of control over the position of the ore bodies. The present writer believes that the ore bodies as a whole in this vein occupy a position along the vein that coincides with the expectable position of "openings"

[8] Ore deposits of the Western States. Lindgren Volume, A. I. M. E., 1933, pp. 638–639.

[9] Ferguson, H. G.: Geology and ore deposits of the Mogollon mining district, New Mexico. U. S. Geol. Surv. Bull. 787: 76–78 and figures, 1927.

FIG. 5. Plan and vertical projection, little Fanney Mine, Mogollon, New Mexico, by Ferguson. U. S. Geol. Surv. Bull. 787.

in a curved fault of this shape and with this kind and general amount of movement.

Two assumptions on which this rests are that the stoped areas represent the approximate position of the ore above the 900-foot level, and that the different levels approximately follow the vein

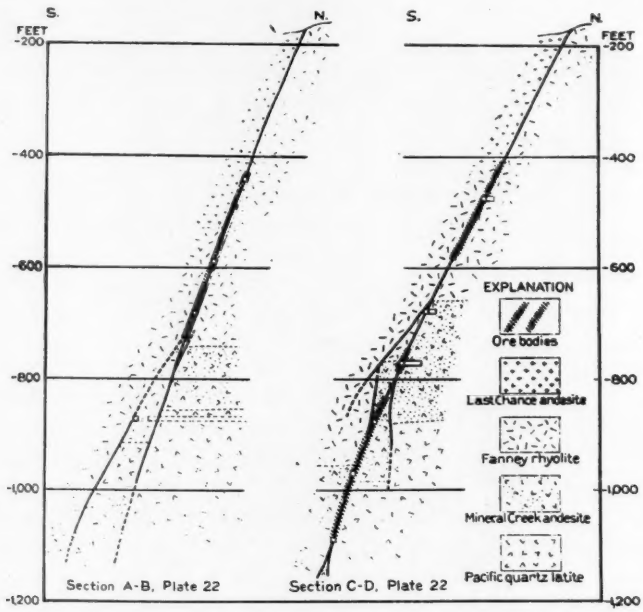


FIG. 6. Transverse section, Little Fanney Vein, Mogollon, New Mexico, by Ferguson. U. S. Geol. Surv. Bull. 787.

and may consequently be used as contour lines. In Fig. 7 the writer traced the solid lines on the levels shown on the plan (Fig. 5) and interpolated with dashed lines. The approximate position of the stoped portions of the vein was taken from the vertical projection, Fig. 5. The resulting figure is regarded as a plan showing approximately the contours of the vein.

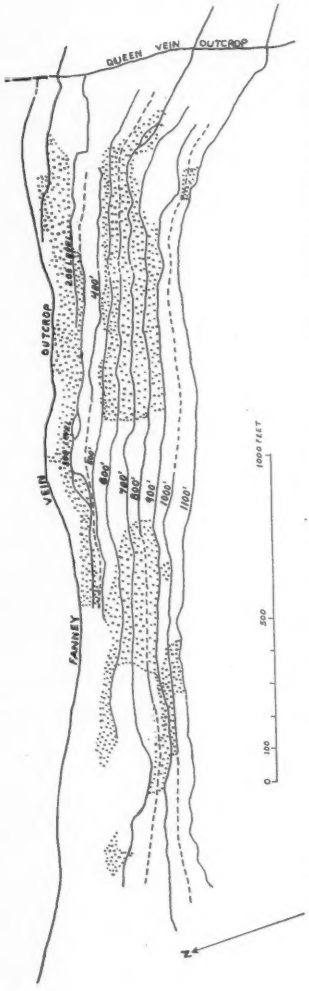


FIG. 7. Contour map of Little Fanney Vein, Mogollon, New Mexico. Solid lines drawn on levels. Dashed lines interpolated contours. Stoped areas to date of Ferguson's report shown by dots.

Analysis of Vein Contour.

Whole Ore Zone.—The ore bearing zone above the 900-foot level appears to lie in an area of the fault that shows favorable changes in (*b*) dip along the line of strike, (*c*) strike along the line of dip, and (*d*) strike along the line of strike, as in Fig. 3*f*. The favorable change of dip along the strike is suggested by the spread of the levels or contour lines at both the east and west ends of the ore zone. At the east end near the trace of the Queen vein outcrop, the lines on the 200-foot level and the unnumbered level above it diverge eastward from the 1100 level line. At the west end, divergence westward is present betwen the 700 level line and the 1100 level line. It is suggested that these end areas are regions of low dip compared with the dip of the ore-bearing zone as a whole. (*c*) The favorable change of strike along the line of dip is outlined at the extreme limits shown on the plan by comparison at corresponding places along the line of dip. Comparison is made of the line along the 1100 level and that on the 200 level at the east end of the mine, as well as the unnumbered one above it, also at the west ends of the 600 and 700 level lines.

The end areas would tend to form "bearing" or supporting zones in a normal fault as would also the unstoped area in the central part of the mine lying between the 500 level and the 1100 levels.

Individual Stoped Areas.—Information is lacking for an analysis of the fault deviations connected with the stoped area above the 300 foot level.

The stoped area below the 400-foot level at the east end of the mine lies in a zone of favorable change of strike along the line of dip and of favorable change of dip along the strike. The lines on the 400 or 500 levels when compared with those on the 900 or 1100 levels indicate both these features. The part of the western stoped area lying between the 600 and 900 levels lies in a similar favorable change of dip along the line of strike. In brief, these two large stoped areas lie in smaller curves that mimic the large one containing all the stoped areas. The influence of change of dip along the line of dip is apparently only local.

ORE DEPOSIT IN REVERSE FAULT.

The Sixteen to One mine, Alleghany District, California is given as an example. The data are taken from Ferguson's excellent report.[10] This gold-quartz vein is in a reverse fault, with mineralization of mesothermal type. The mine has been the most productive in the district, with the greater part of the production from between the Sixteen to One shaft and the Compromise raise, that is, the two southernmost stoped areas shown on Fig. 8. The gold is later than the early quartz. On the whole the quartz is thickest in the flatter portions of veins that follow reverse faults in this district.[11] This is suggestive, as Ferguson remarks, of the filling of open spaces, but as he points out may indicate not actual open spaces but merely areas in which compression was less severe.

The displacement on the reverse fault that is followed by the Sixteen to One vein as measured along the dip, ranges from 900 feet along the line C–C′ (Fig. 8) to less than 500 feet in the northern part along A–A′ and less than 300 feet in the southern part along G–G. The dip varies greatly from less than 20° to 60°, but over most of the productive part of the mine the prevailing dip is between 25° and 30° E. Little high grade ore has been obtained from the large lenticular swellings of quartz, but their edges where they fade out along the strike have been very productive.

Analysis of Vein Contour.

Whole Ore Zone.—In this discussion the high grade ore shoots are not distinguished from those of lower grade (Fig. 9). The mined areas as a whole appear to lie in a curved area (Fig. 3*h*) and in addition occupy a favorable change of dip up the dip. It is suggested that areas of compression or supporting surfaces are being approached in several big areas on the border of the ore bearing zone. The combined change of (*b*) dip along strike, and (*c*) strike along line of dip suggest that the South end and the

[10] Ferguson, H. G.: Gold-quartz veins of the Alleghany district, California. U. S. Geol. Surv. Prof. Pap. 172: 28–86, 106–109, 1932.

[11] Op. cit., p. 81.

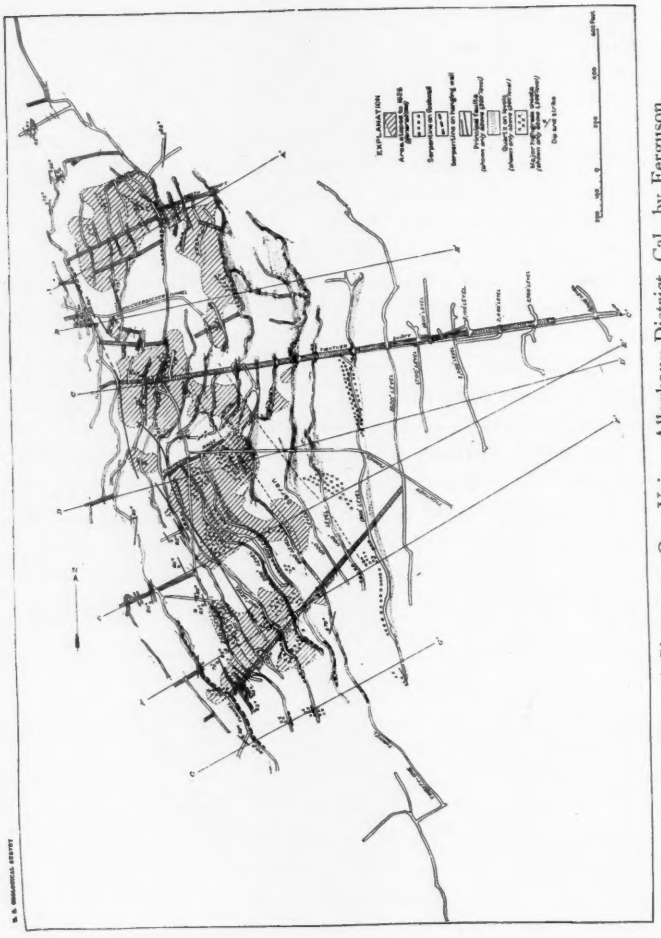


FIG. 8. Plan of Sixteen to One Vein. Alleghany District, Cal., by Ferguson. U. S. Geol Surv. Prof. Paper 172, Plate 53.

upper part of the North ends of the zone that produced ore, are entering zones of compression or bearing areas unless they change farther out.

Individual Stoped Areas.—The present writer has little information on level elevations in the north half of the mine above the 1000-foot level. Only the two southernmost stoped areas will be discussed.

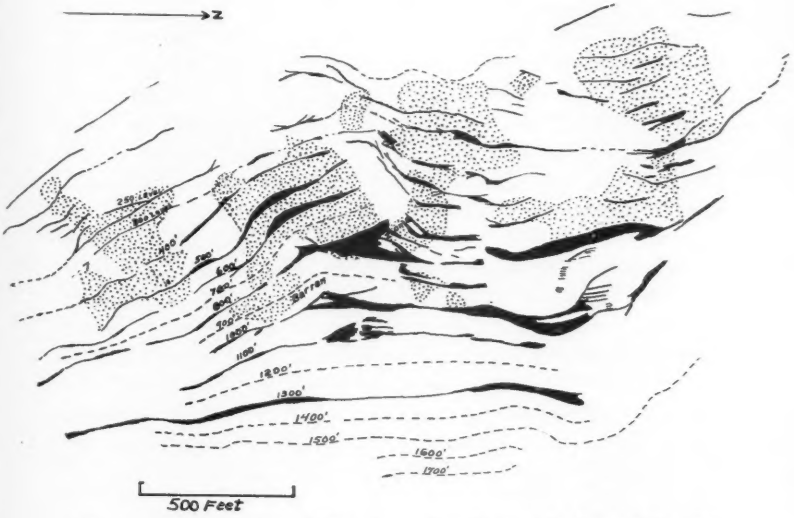


FIG. 9. Contour map of Sixteen to One Vein, Alleghany Dist., Cal. Generalized position of stoped areas to year 1925 indicated by dots. Black lines and areas show quartz above 1300 ft. level. Dashed lines are interpolated contours.

The stoped area in the southern end of the mine is outlined by favorable changes in (*b*) dip along strike, and (*c*) strike along line of dip. These, although not pronounced, are analogous to those of the main zone. This favorable warp is outlined by the lines on the 250-foot level and on the 600 or 800 levels. The trends of the 300 and 400 level lines through the stoped area suggest the same feature.

FIG. 8. Plan of Sixteen to One Vein. Alleghany District, Cal., by Ferguson. U. S. Geol Surv. Prof. Paper 172, Plate 53.

The second stoped area from the south end of the mine shows similar features as outlined by the 1200- and 1300-foot lines and the 300- and 400-foot lines. The heavier quartz veins in this area are apparently in the more accentuated parts of the curve.

CONCLUSIONS.

The qualitative treatment that has been given could be made quantitative by graphic or mathematical means.

However, other factors besides geometry enter into any consideration of the "openings" that may be produced. Even if the opening that is formed by any one pulsation of fault movement is not wide, minor bridging must take place where the rocks settle or give way here and there to the pressure normal to the fault. This would be expected particularly with a large favorable curve extending for hundreds of feet along a vein. Where the pressure normal to the fault is great and the rocks weak, favorable curvature would be expected not to give openings, but only zones of lower compression than elsewhere along the fault. This partial accommodation of one irregular surface to another might be accomplished by flowage, fracturing or faulting or some combination of these. The subsidiary faults related in part or wholly to such action would form an interesting and commercially profitable subject for inquiry. What are their attitudes with respect to the geometric features of the main fault and the direction of movement along it?

ACKNOWLEDGMENTS.

The writer is indebted to C. H. Behre, Jr., A. E. Buller, R. D. Butler, J. E. Hawley, T. S. Lovering, W. J. Mead and R. R. Shrock for suggestions on the preparation of this article. Figures 1–4 inclusive were drawn by A. E. Buller.

MASS. INST. OF TECHNOLOGY,
CAMBRIDGE, MASS.,
March 4, 1940.

DISCUSSION AND COMMUNICATIONS

THE GEOCHEMISTRY OF QUICKSILVER MINERALIZATION.[1]

Sir.—The paper " The geochemistry of quicksilver mineralization " by Robert M. Dreyer in recent numbers of this journal[2] is a comprehensive treatment of a subject on which there is a deplorable dearth of definite information. It does a distinct service in the assembly of references to the literature that bears on the problem. Dreyer's discussion, however, appears to us to include interpretations and conceptions that call for some discussion.

He subscribes to the view, which has long been generally accepted, that mercuric sulphide is precipitated from hydrothermal alkaline sulphide solutions at temperatures of 100°–150° C. and at pressures close to atmospheric. He discusses at length the fact that mercuric sulphide is soluble in alkaline solutions and insoluble in neutral and acid solutions, but states on page 36 that " increased acidity is not generally a common cause of the precipitation of mercuric sulphide." It would seem, however, that an increase in acidity, *i.e.*, a partial neutralization of the alkaline sulphide solution, affords a simple and adequate mechanism for the precipitation of mercuric sulphide. Any assumption that such a process does not commonly take place under natural conditions requires the support of more positive field evidence than has yet been presented.

One of Dreyer's reasons for disbelief in the efficacy of acidification is the rarity of metacinnabar in quicksilver deposits. His argument on this point, among others, rests largely on an apparent misinterpretation of the experimental work of Allen and Cren-

[1] Published with the permission of the Director, U. S. Geological Survey.

[2] Dreyer, Robert M.: The geochemistry of quicksilver mineralization. Econ. Geol., 35: 17–48, 140–157, 1940.

shaw.[3] He seems not to have realized the meaning of their proof, which he accepts, that metacinnabar is a monotropic form of mercury sulphide. The fact that metacinnabar is a monotropic form means simply that it is metastable with respect to cinnabar under all conditions. Theoretically, therefore, metacinnabar is always changing to cinnabar, and statements such as those by Dreyer, that " cinnabar will be deposited only from markedly alkaline solutions " (p. 44) and " metacinnabar could be converted to cinnabar only by the action of hot alkaline solutions " (p. 48), are incorrect. The same objection applies to his statement on page 44, that, " in so far as the study of quicksilver mineralization is concerned, marcasite, like pyrite is stable over the entire range of possible physical conditions," as marcasite is monotropic with respect to pyrite.

It is true that often the rate of transformation of a monotropic substance is so slow that the substance is for all practical purposes stable. From this standpoint, the foregoing discussion might be considered merely academic. It is important, however, to realize that laboratory experiments on the conditions under which monotropic substances are formed merely give indications as to the rate of the transformation into the stable form under certain specified conditions; furthermore, it is well known that slight changes in conditions, for example the presence of small amounts of certain impurities, may have an important effect in determining which of two polymorphous forms is precipitated.[4] It must also be borne in mind that laboratory experiments, performed in the limited time that marks the duration of all human endeavor, only point the way to an understanding of processes that continue through geologic time. For these reasons, it is necessary to use considerable caution when applying the results of laboratory experiments to geological problems, and particularly to those in which monotropic substances are involved.

Dreyer cites the work of Allen and Crenshaw as showing " that in acid solutions above 200° C. and in alkaline solutions above

[3] Allen, E. T., and Crenshaw, J. L.: The sulphides of zinc, cadmium, and mercury: their crystalline form and genetic conditions. Am. Jour. Sci., 4th ser., 34: 341–96, 1912.

[4] See, for example, Bloom, M. C.: The mechanism of the genesis of polymorphous forms. Amer. Min., 24: 281–92, 1939.

100° C., metacinnabar is converted to cinnabar" (p. 34). In his discussion of the citation he evidently considers these temperatures as fixed transition points. Thus he says (pp. 35–36), "Were increased acidity an important precipitating agency, despite the absence of metacinnabar in most deposits, one of the following changes must have occurred: (1) A temperature above 200° C. must have existed . . . (2) A new influx of alkaline sulphide solutions would be needed." From what has been said, it is obvious that 100° and 200° C. are not, as Dreyer evidently assumes, fixed transition temperatures but merely the temperatures at which metacinnabar is converted to cinnabar at a reasonably rapid rate under certain specified conditions. Turning to the paper by Allen and Crenshaw, we find (p. 378) that they report (1) that metacinnabar, heated at 100° C. for an unspecified time with $(NH_4)_2S$ of unspecified concentration, was completely converted to cinnabar; (2) that metacinnabar, heated at 200° C. for 4½ days with 30 per cent H_2SO_4, was about 10 per cent changed to cinnabar. All that these experiments indicate is that the transformation of metacinnabar is accelerated by the presence of alkaline sulphide solution and retarded by the presence of much acid. Statements such as those of Dreyer on p. 35, "that, in acid solutions below 200° C., only metacinnabar is precipitated" and "similarly, metacinnabar is converted to cinnabar in alkaline sulphide solutions at about 100° C." are meaningless, even when limited to laboratory results, unless the exact concentration of alkaline sulphide or of acid is specified.

Apparently Dreyer believes that those who advocate precipitation of mercury sulphide by acidification imply that the solution must become strongly acid. Such a condition is not necessary to accomplish the precipitation of HgS, as may readily be seen from the table below, which is part of Knox's data at 25° quoted by Dreyer (his table 3, p. 29).

Concn. Na_2S moles/liter	HgS dissolved in pure Na_2S (moles/liter)
1.015	0.4423
0.50	0.1500
0.25	0.0454*
0.10	0.0082

* This is misprinted as 0.454 in Dreyer's paper.

Consider the neutralization of the most concentrated solution of the table above. When half the Na_2S has been neutralized, 29/44, or nearly 66 per cent, of the HgS will have been precipitated. If three-fourths of the Na_2S is neutralized nearly 90 per cent of the HgS will have been precipitated, and the solution still contains 0.25 moles of Na_2S (= 19.5 g.) per liter. If nine-tenths of the Na_2S is neutralized, over 98 per cent of the HgS will have been precipitated, and yet the solution still contains 7.8 g. of Na_2S per liter and is a decidedly alkaline solution. The proportion precipitated would be of the same order of magnitude if the original solution were of some other concentration or if it contained free alkali (see Dreyer's Tables 1, 2 and 3, pages 28 and 29). It is apparent that Dreyer's statement (p. 35) that "The scarcity of metacinnabar suggests that increased acidity is not an important factor in the precipitation of most mercury ores" has no basis in fact, because, as shown above, nearly all the mercuric sulphide precipitated by acidification of the solution would be precipitated from solutions still strongly alkaline. Furthermore, such acidification would cause the precipitation of silica along with the mercuric sulphide.

Dreyer states (p. 30)—"The carbonatization associated with some quicksilver ores must thus have been accomplished at a time when the mineralizing solutions were slightly acid and must thus be distinct from the period of cinnabar deposition." This view, repeated in different words on page 141, will doubtless come as a surprise to most geologists and chemists, as the fact that alkaline solutions can contain calcium bicarbonate scarcely needs to be demonstrated. Incidentally the sentence quoted above would be more easily understood if rephrased somewhat as follows: "The carbonate minerals associated with some quicksilver ores must thus have formed at a time when the mineralizing solutions were slightly acid and these minerals cannot, therefore, be syngenetic with the cinnabar." Similar confusion between processes and the results of the processes is common throughout Dreyer's paper.

Dreyer's reasons (p. 38) for dismissing reductions by organic compounds as a cause for the occurrence of native mercury are not convincing. Coal and charcoal, which are the only organic substances considered by Dreyer, are much weaker reducing

agents than many of the bituminous substances found associated with cinnabar. The significance of the presence of such substances in most quicksilver lodes has not as yet received adequate study.

The second part of the paper consists mainly in the application of the chemical concepts outlined in the first part to certain quicksilver mining districts. The basis is the petrographic study of specimens from these districts supplemented by detailed geologic field work only in the Goldbanks district, Nevada.[5] Valuable ideas are contributed but the paper needs to be read with care and discernment in order to view these ideas in proper proportion.

The Goldbanks district is a minor representative of a numerous but little known group of quicksilver deposits, mainly in northern Nevada and southern Oregon, popularly known as "opalite" deposits. These deposits are so different from many of those in California and other States that inferences based on observations at Goldbanks may not be applicable to other kinds of deposits. At Goldbanks the cinnabar is in a siliceous spring sinter but this association is not necessarily indicative of a universally close relation between cinnabar and silica. Chalcedony, opal, and quartz are abundant in some of the deposits in California. These minerals are, however, in part so much older than the cinnabar as to suggest that they have a different genetic significance in California than they do at Goldbanks. In some of the Californian and Texan deposits carbonates are far more conspicuous components of the gangue than silica minerals are.

The intimate mixture of pyrite and marcasite with cinnabar and metacinnabar in the ore of the Mount Diablo mine, Cal., certainly suggests changes in the character of the solutions during deposition, but lends little support to Dreyer's conclusions as to the mode of origin of the different forms of mercuric sulphide. His argument that part of the iron disulphide crystallized later than the mercuric sulphide minerals is sound, but there is equally good evidence that part of the pyrite and marcasite formed earlier.[6]

[5] Dreyer, R. M.: Goldbanks mining district, Pershing County, Nevada. Univ. of Nevada Bull. 34, no. 1: 1–36, 1940.

[6] Ross, C. P.: The Mount Diablo quicksilver district, Contra Costa County, California. U. S. Geol. Surv., in preparation.

Dreyer on pages 151 to 155 contends that replacement was a major factor in the formation of many quicksilver deposits, in contrast to Becker's concept that essentially all cinnabar has been deposited in open space.[7] Becker's statements may be too sweeping but the difference between his views and Dreyer's is in part a matter of definition. Dreyer says that the present concept of replacement involves "large scale solution and redeposition," whereas Becker regarded it "as a process of molecular interchange." Becker's concept of the process is still essentially the generally accepted one as is attested by Lindgren's recent statement[8] that replacement is "the process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly different chemical composition may grow in the body of an old mineral or mineral aggregate." As Dreyer says near the bottom of page 154, most of the cinnabar in ordinary quicksilver ore fills intergranular openings and fractures that existed prior to mineralization. The limited amount of cinnabar formed by replacement, in the unusual sense in which Dreyer defines this term, differs in mode of emplacement only in that it fills openings formed chemically at some stage prior to the deposition of the cinnabar instead of mechanically before mineralization began. The facts that Dreyer presents on the basis of his microscopic observations could be explained on the assumption that there was an appreciable time interval between creation of the openings and crystallization of the cinnabar. As thus viewed, the arguments put forth by Dreyer are not so much opposed as they might appear at first glance to the essential concept that in most kinds of quicksilver lodes ore of commercial value is localized only where abundant open spaces were available at the time that the cinnabar crystallized.

JOSEPH J. FAHEY,
MICHAEL FLEISCHER,
CLYDE P. ROSS.

WASHINGTON, D. C.,
April 6, 1940.

[7] Becker, G. F.: Quicksilver deposits of the Pacific slope. U. S. Geol. Surv. Mon. 13: 30, 315, 394–401, 1888.

[8] Lindgren, Waldemar: Mineral Deposits, 4th edit., p. 91, 1933.

REVIEWS

Geology and Engineering. By ROBERT F. LEGGET, with a foreword by P. G. H. Boswell. Pp. 642; Figs. 225. McGraw-Hill Book Company, New York, 1939. Price, $4.50.

This book differs from others on the same general subject in that it is written by an engineer with additional training in geology, whereas all the others are by geologists. The author states that his book is not for geologists but for engineers; the reviewer commends it to both groups, with certain reservations. The engineer who lacks training in geology will find it inadequate for his needs in some respects, but he will be deeply impressed with the need for geologic advice in many of his undertakings. The inadequacy lies more in the character of the subject than in the treatment, for it seems impossible to combine the fundamentals of physical geology with a thorough treatment of their application in a single book or in a single course.

Part I, a brief introduction to geology, can safely be passed over by the geologist reader. It will be of interest to the engineer but seems to be too brief (54 pages) to give him an adequate background of knowledge for the far more important Part II on "Geology as applied in civil engineering."

Part II begins with chapters on the relationships between civil engineering and geology and on preliminary and exploratory work. Both should be read by geologist and engineer alike. They are followed by a clear discussion of geophysical methods and their adaptability to various types of engineering work. The remaining thirteen chapters of Part II will surprise many geologists in the diversity of engineering problems that touch on geology. In addition to chapters on dam and bridge foundations, there are discussions of tunnels, open excavation and embankments, transportation routes (roads, railways, harbors, and airports), reservoirs, building foundations, and construction materials.

Interspersed with these objective chapters are more subjective discussions of earth movement and landslides, erosion and silting, water supply, groundwater, and soils and soil mechanics. This treatment, though possibly unavoidable, will probably be less confusing to the geologist than to the engineer, who may fail to realize how many geologic factors are likely to be involved in a single dam site, for instance. The chapter on soils,

incidentally, includes extensive discussions of rock weathering and of glaciers and their products.

Each chapter deals with the subject matter clearly and, with few exceptions, as fully as possible in a work of this size and scope. The chapter on tunnels, for example, will give the thorough reader not only a knowledge of the principal geologic factors that are likely to affect tunneling operations, but of many ingenious methods that have been adopted by engineers to overcome the difficulties imposed by local geologic features.

The general statements are given point by a profusion of actual examples drawn from world wide sources. These examples are so numerous and so closely interwoven with the generalizations that a reader in search of specific information may find it necessary to read entire chapters that cover his interests of the moment; however, the examples, together with the numerous well chosen illustrations, constitute much of the book's value. Not only do they provide factual information of the greatest importance, but they afford a rich source of illustrative material for the teacher. In particular, they will add spice to the geologic sauce for those student minds that require practical value in the sciences they study.

Several gaps in the record, many of them doubtless owing to lack of space, will be apparent to the thoughtful reader; for example, there is no explicit warning that grouting can actually be done at too high pressures and so force the rocks apart. Similarly, there is no statement that post-construction enlargement of leaks in limestones that form the foundations of dams is more often due to removal of clay fillings in old caves rather than to continued solution. There is lack of emphasis on the effect of local structural conditions in discussions of drill core recovery, of uplift pressures, and of other subjects.

The book closes with a series of appendices which include an excellent glossary of geologic terms, brief details regarding the geological surveys, societies, and publications of the English speaking world, and a bibliography of more than 300 titles of papers referred to in the text. This bibliography, with the lists of reference works at the end of each chapter, forms an important part of the work.

Geology and Engineering can scarcely be recommended as a text for a beginning course in geology for engineers; however, for more advanced students or for the practising engineer who possesses the fundamentals of geology, it has much to commend it. It should be read and absorbed by every geologist who has anything to do with engineering work, and it should prove invaluable to everyone who teaches geology to engineers.

EDWIN B. ECKEL.[1]

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

[1] Published by permission of the Director, U. S. Geological Survey.

Finding and Producing Oil. AMER. PETROL. INST., Dallas, Texas, 1939. Pp. 338. Price, $3.00.

This is an excellent concentrated manual on finding and producing oil prepared by the Institute, assisted by 15 authors. There are 15 sections in which are included Geological Methods (46 pp.), Geophysical Methods (16 pp.), Drilling, Sampling, Coring, Surveying, Production, Testing, Training, Laws, Associations, Societies, Manufacturers, Drilling Contractors, and Fundamental Research. Good reference lists accompany each section, some of which are longer than the articles they amplify. As an illustration of the compactness, only one page each is devoted to electrical logging, gravitational methods and reflection methods of geophysical prospecting. Obviously, details are lacking—purposely. That is why it should prove a handy reference to one who wishes, first, a general viewpoint and second, where to turn for detail.

Textbook of Geology. Part I, Physical Geology, 2nd Edit. By C. R. LONGWELL, A. KNOPF AND R. F. FLINT. Pp. 543; Figs. 340. John Wiley and Sons, New York, 1939. Price, $3.75.

This is the second edition and revision by the present authors, of the former well established textbook of the same name by L. V. Pirsson. The revision follows the general plan of its predecessor but it shows an increase of 29 pages. Two chapters have been added, one on "mass-wasting," an excellent addition, and one unifying land sculpture by running water. Other chapters have been considerably revised or reorganized, the newer material in geology has been added, and there is notable improvement in illustrations. The book maintains its place as the leading textbook in physical geology.

The Throne of the Gods. By ARNOLD HEIM AND AUGUST GANSSER, translated by Eden and Cedar Paul. Pp. 235; Figs. 220; Map. Macmillan, New York, 1939. Price, $5.00.

This book is a popular by-product of the Swiss Geological expedition to the little known parts of the Central Himalayas. The strictly scientific research that resulted from the expedition is reserved for another volume and this one deals wtih the country, the people, the animals, the plants and the experiences and discoveries of the authors in the mountains in Tibet and Nepal. Naturally, quite a little geology has slipped in. The many photographs are sketches truly remarkable and are in themselves a liberal education. The book is delightfully written and the story is entrancing.

Textbook of Paleobotany. By W. C. DARRAH. Pp. 441; Figs. 180. Appleton-Century Co., New York, 1940. Price, $6.00.

This is another volume of the Botanical Publications in The Century Biological Series by Professor Darrah of Harvard. Botany and geology are interwoven in this introductory paleobotany but the reader is assumed to have some knowledge of introductory botany and historical geology and the viewpoint is dominantly geological. There are four parts: (1) General Principles (including the paleobotany of coal), (2) The Paleontological History of the Vascular Plants, (3) The Succession of Ancient Floras (Paleozoic, Mesozoic, Cenozoic and Present), and (4) General Results. The illustrations are good but sparse. The book is well written, thoroughly up-to-date and the material is well organized.

BOOKS RECEIVED.

DAVID GALLAGHER.

Relatorio da Diretoria, 1937. A. I. DE OLIVEIRA. Pp. 227; pls. 14. Serviço de Fomento da Produção Mineral, Bol. 31. Rio de Janeiro, 1938. *Occurrence and production data on minerals alphabetically arranged; register of mining companies; statistics.*

Rutilo em Goiaz. O. H. LEONARDOS. Pp. 96; pls. 28; geologic map in color, 19″ × 19″, scale ca. 1.36″ = 50 kms. Serv. de Fom. da Prod. Min., Bol. 30. Rio de Janeiro, 1938.

Rochas da região de Bragança a Turí-assú. H. C. A. DE SOUZA. Pp. 36; pls. 6; 1 map. Serv. de Fom. da Prod. Min., Bol. 32. Rio de Janeiro, 1938.

Contribuição para a Geologia do Petroleo no Sudoeste de Mato Grosso. G. DE PAIVA AND V. LEINZ. Pp. 98; figs. 7; pls. 6. Serv. de Fom. da Prod. Min., Bol. 37. Rio de Janeiro, 1939.

Gipsita. T. DE M. MORAES. Pp. 15; figs. 3; pls. 4. Serv. de Fom. da Prod. Min., Avulso 35. Rio de Janeiro, 1938.

O Inlandsis Permo-Carbonifero do Sul do Brazil. G. DE PAIVA. Pp. 34; figs. 2. Serv. de Fom. da Prod. Min., Avulso 36. Rio de Janeiro, 1938.

Columbita e Tantalita no Rio Grande do Norte. H. C. A. DE SOUZA. Pp. 16; 1 pl.; 1 map. Serv. de Fom. da Prod. Min., Avulso 38. Rio de Janeiro, 1939.

Beneficiamento da Apatita em Ipanema, Estado de São Paulo. J. B. DE ARAUJO. Pp. 19; two flow sheets. Serv. de Fom. da Prod. Min., Avulso 39. Rio de Janeiro, 1939.

The Mineral Deposits of the Murchison Range, East of Leydsdorp. O. R. VAN EEDEN, F. C. PARTRIDGE, L. E. KENT, AND J. W. BRANDT. Pp. 172; pls. 10; figs. 13; geologic map in color, 32″ × 25″, scale 1:100,000. South Africa Geol. Surv., Mem. 36. Pretoria, 1939. Price, 7s, 6d. *Detailed and interesting tectonics and igneous geology, complex antimony-gold-copper ores, and pegmatite deposits.*

Report upon the Mining Industry of Malaya. L. L. FERMOR. Pp. 240; figs. 7; two maps in color, geographic 16″ × 22″, scale 1″ = 18 miles, geologic 24″ × 33″, scale 1″ = 12 miles. Federated Malay States Gov't Press, Kuala Lumpur, 1939. Price, $2.50 or 6s. *A comprehensive treatise that should be one's first reference on the Malay. Covers general geology, economic development of the country, mining methods, regulations and laws, relations of mining to other industries, the mines department and the geological survey, prospecting, mine finance, tin ores, other minerals, power, government policy with respect to mineral exploitation, etc., etc., together with recommendations.*

Gmelins Handbuch der anorganischen Chemie—Platin. E. PIETSCH ET AL. System Nr. 68. Teil A, Lieferung 2; Vorkommen (Abschluss); Pp. 170; 1 fig. Price, RM 19.50. Teil B, Lieferung 2; Physicalische Eigenschaften des Metalls (bis elektrische Eigenschaften); Pp. 110. Price, RM 12.75. Teil B, Lieferung 3; Elektrochemisches Verhalten des Metalls (Überspannungserscheinungen); Pp. 84; figs. 47. Price, RM 10.50. Verlag Chemie, G.m.b.H., Berlin, 1939. *Treats the subject of platinum with typically Germanic detail and exhaustive thoroughness.*

El Mineral de Plomo (Galena) de Poscaya (Salta)—Información sumaria de Geologia Económica. L. R. CATALANO. Pp. 46; 68 photographs. Inst. de Fisiografía y Geol., V. Rosario, Argentina, 1939.

Geologic Map and Guide of Oahu, Hawaii. H. T. STEARNS. Pp. 83; pls. 6; figs. 22; geologic map in color, 44″ × 33″, scale 1:62,500. Hawaii Div. of Hydrography, Bull. 2. Honolulu, 1939. *Guide to the geology along the main highways, together with a chapter on the mineral resources. Outstanding for its unique and exceptionally fine pen and ink diagrams and for the excellence of its photographs.*

The Geology and Mineral Deposits of the Oliphants Hoek Area, Cape Province. F. C. TRUTER, B. WASSERSTEIN, P. R. BOTHA, D. J. L. VISSER, L. G. BOARDMAN, AND G. L. PAVER. Pp. 142; pls. 13; figs. 17; tables 6; three geologic maps in color, main geologic map 32″ × 20″, scale 1:125,000, geologic map of the iron and manganese occurrences, 13″ × 18″, scale 1:59,500, geologic map of the Farm Bishop, 8½″ × 13½″, scale 1:7438. South Africa Geol. Surv., An Explanation of Sheet No. 173, Oliphants Hoek. Pretoria, 1938. Price, 5s. *Transvaal and Waterberg systems, Karroo dolerites, kimberlites, crocidolite deposits, iron and manganese deposits and others, and ground water.*

Código de Minas (Decreto No. 24.642 de 10 de Julho de 1934) Leis e Regulamentos Subsequentes. Pp. 105. Serv. de Fom. da Prod. Min., Avulso 34. Rio de Janeiro, 1938. *Brazilian Mining Law.*

Mississippi Geol. Surv., 17th Biennial Report. W. C. MORSE. Pp. 14. University, 1939. *Report of progress, administrative.*

Geology of the Kaitangata-Green Island Subdivision, Eastern and Central Otago Divisions. M. ONGLEY. Pp. 96; pls. 5; figs. 7; tables 11; 1 index map; 9 geologic maps in color, scale 1:63,360, covering about 1000 square miles southwest of Dunedin. New Zealand Geol. Surv., Bull. 38. Wellington, 1939. Price, 10s, 6d. *General description, including geology and physiography, of a region of sediments including coal, clay, and sand deposits.*

SCIENTIFIC NOTES AND NEWS

E. L. DEGOLYER gave the dedication address at the opening on March 15 of Berthoud Hall, the new geology-geophysics building at the Colorado School of Mines.

GILBERT WILSON has recently been appointed to the department of geology of the British Imperial College of Science and Technology.

A. I. LEVORSEN, consulting petroleum geologist of Tulsa, Oklahoma, delivered three lectures on petroleum geology at the Univ. of Chicago and Northwestern University in March.

G. S. HUME, of the Canadian Geological Survey, delivered three lectures on Canadian and world problems in petroleum at Queen's University, Kingston, during March.

R. A. PELLETIER has been elected President of the Geological Society of South Africa. The Society has awarded its Draper Memorial Medal to H. S. HARGER.

THE PENNSYLVANIA GEOLOGISTS 1940 ANNUAL CONFERENCE will be held May 30 to June 2 with registration at the Cochrane House, Newton, N. J. May 30, 8.30 A.M. leave for Culvers Gap, McAfee Quarry and via Franklin and Stockholm to Newfoundland. May 31 leave for Franklin zinc deposits, Dover magnetite mines, ending at New Brunswick (also possible alternate trip). June 1, coastal plain geology and to Cliffwood for lunch.

E. N. PENNEBAKER, geologist for Cons. Coppermines Corp., is in Cuba on professional work.

H. RIES lectured on Engineering Geology Features on the West Coast to the department of geology at the Univ. of Toronto on March 14.

O. A. LAMPE and ALFRED WANDKE who have been with Guanajuato Cons. Min. and Milling Co. for many years are developing the "Compañía Minera de Guadalupe of South America."

M. D. GARRETTY has been appointed chief geologist for North Broken Hill, Ltd., New South Wales.

SIDNEY PAIGE is in the Canal Zone as consultant on geologic problems connected with the third lock system. He will return to New York late in May.

A. K. SNELGROVE, instructor in geology at Princeton, has been appointed head of the department of geology and mineralogy at Michigan College of Mining and Technology.

W. H. BRADLEY, of the U. S. Geological Survey, was presented at the 297th meeting on March 21 of the Washington Academy of Sciences the award for scientific achievement in the physical sciences in recognition of his contributions on the oil shale of the Green River formation of Wyoming.

J. B. GOWAN, JR., geologist for Anaconda Copper Mining Co., has returned from Poland to the Butte office.

J. B. HANLEY has been appointed assistant state geologist of Arkansas.

FREDERICK SIMONDS, professor of geology at the Univ. of Texas for half a century, was recently honored by an anniversary banquet tendered by the geological staff and friends.

ADVERTISEMENTS

Patrons of this journal are requested to refer to ECONOMIC GEOLOGY when consulting advertisers.

A Complete Plant Under One Roof

PRINTING ~ BINDING ~ ELECTROTYPING

Printers of
Scientific and Technical Journals and Books
Theses and Dissertations
Works in Foreign Languages

Your Book, Journal or Thesis placed with us insures that the composition, proof-reading, electrotyping, presswork and binding follow through in consecutive order in one plant—established sixty-three years ago—and under the supervision of one management. : : :

LANCASTER PRESS, Inc.

Established 1877 **LANCASTER, PA.**

[*Printers of Economic Geology*]

Minerals and Rock Specimens

Large variety of MINERALS by weight for class work and for laboratory purposes. Freight paid on all shipments valued at $25 and over.

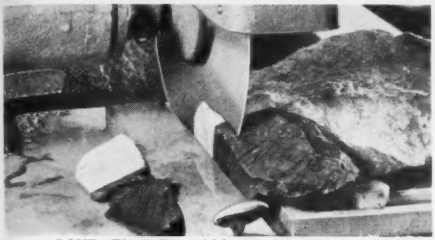
R. M. WILKE, Box 312 **PALO ALTO, CALIF.**

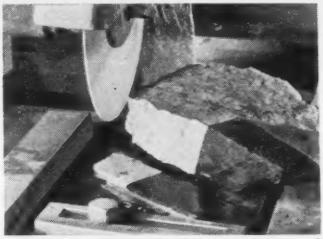
VOL. XII, NO. 1
of the
ANNOTATED BIBLIOGRAPHY OF ECONOMIC GEOLOGY
is now ready to mail
Price $5.00
Order from
ECONOMIC GEOLOGY PUBLISHING CO.
URBANA, ILL.

THIN - SECTIONS
AND
POLISHED SECTIONS

Prices reasonable

RUDOLPH VON HUENE
281 S. HUDSON AVE.
PASADENA, CALIF.

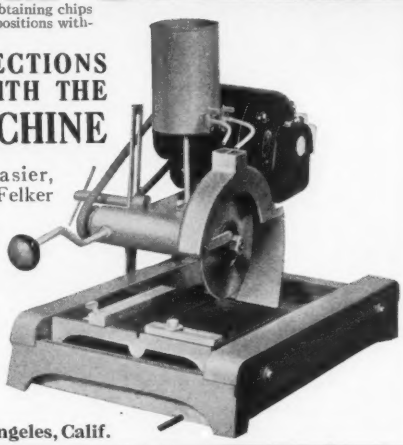




ABOVE: The Felker Di-Met Machine permits obtaining chips from contact sections from the most favorable positions without damaging the specimen.

CHIPS FROM CONTACT SECTIONS ARE EASILY OBTAINED WITH THE FELKER DI-MET MACHINE

Petrographic work is prepared easier, quicker and more accurately with the Felker Di-Met Machine equipped with the Felker Di-Met diamond-impregnated blade. Saw cuts from rocks are obtained without the use of clamps or special mountings. The Felker Di-Met Machine is simple and safe to operate and is unusually clean in operation. Write for Bulletin Pl-39.



MUSTO-KEENAN CO.

Sales Division - 1801 So. Soto St., Los Angeles, Calif.

REVUE DE GEOLOGIE et des Sciences connexes
RASSEGNA DI GEOLOGIA e delle Scienze affini
REVIEW OF GEOLOGY and Connected Sciences
RUNDSCHAU FUR GEOLOGIE und verwandte Wissenschaften

Published monthly with the cooperation of the Fondation Universitaire de Belgique, under the auspices of the Société Géologique de Belgique, with the collaboration of many National Geological Surveys, Scientific Institutions and Geologists throughout the world.

Secrétariat général of the REVUE DE GEOLOGIE: Institut de Géologie, Université de Liége, LIÉGE Belgique).

The REVUE DE GEOLOGIE is par excellence the review of geological reviews; it is not a commercial undertaking, but its aim is to secure a cordial collaboration among geologists of all countries; it publishes summaries of their works and arranges exchanges of documents among its subscribers.

The subscription price of vol. XX (the current volume) is 36 belgas.

Address: M. G. TIBAUX, Treasurer of the REVUE DE GEOLOGIE, 35, rue des Armuriers, Liége (Belgique).

Sample Copy Sent on Request.

SWAN ENGRAVING COMPANY

PHOTO ENGRAVERS COMMERCIAL ARTISTS

BRIDGEPORT, CONN. NEW HAVEN, CONN
POUGHKEEPSIE, N.Y.

AMONG ARTICLES TO APPEAR IN FORTHCOMING ISSUES OF THIS JOURNAL ARE THE FOLLOWING:

Aikenite and Silver Enrichment at the St. Louis Mine, Idaho—A. L. ANDERSON

Ore Deposits at Camp Albion, Colorado—E. E. WAHLSTROM

Minor Elements in Sphalerite—R. E. STOIBER

Mineral Survey in Arkansas—G. C. BRANNER

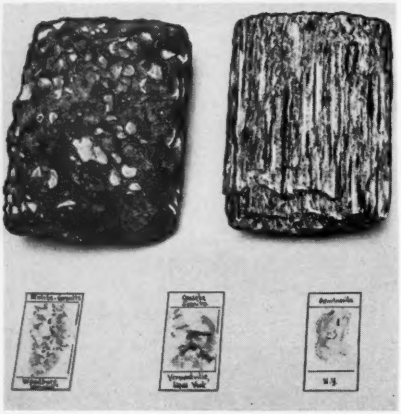
Microscopic Features of Ore from Sunshine Mine—R. J. ANDERSON

Geologic Interpretations from the Pailiviri Section of Cerro Rico de Potosi—D. L. EVANS

Paragenesis in the Hollinger Veins—M. R. KEYS

Magnetite in Sulphide Ores—G. M. SCHWARTZ and A. C. RONBECK

Ground Water in the Oklahoma Panhandle—S. L. SCHOFF



NEW

Ward's Collection of American Rocks

This new collection consists of 100 selected, typical hand specimens including 46 igneous, 32 sedimentary, 22 metamorphic rocks; a complete descriptive manual; and, when desired, 100 expertly prepared thin sections. The set is designed to cover a year's class work in petrology. We invite correspondence concerning this carefully worked out collection and will gladly supply additional information. The collection is prepared and priced in a variety of ways; one of the most suitable is our **WPR-1**, 100 rocks neatly trimmed to standard museum size, 3″ x 4″. Supplied with printed labels, Ward's Improved Specimen Trays and Descriptive Manual. **Per set . . . $60.00.**

WPRs-3, 100 thin sections of above rocks on 26 x 47 mm. Slides in wooden boxes. **Per set . . . $100.00.**

WARD'S NATURAL SCIENCE ESTABLISHMENT, INC.

EST. 1863

290 GOODMAN ST. NORTH - - ROCHESTER, N. Y

THE FRANK A. WARD FOUNDATION OF NATURAL SCIENCE OF THE UNIVERSITY OF ROCHESTER

GEOLOGISCHES ZENTRALBLATT

ABTEILUNG A: GEOLOGY

GEOLOGISCHES ZENTRALBLATT appears on the first and fifteenth of each month in parts containing 4–5 signatures. Nine parts constitute a volume. Fifty-six volumes (1901–1936) have been published.

ABTEILUNG B: PALEONTOLOGY

PALAEONTOLOGISCHES ZENTRALBLATT appears in a single part of 4–5 signatures each month. Eight parts constitute a volume.

The price per volume of the Geologischen Zentralblatt (Abt. A) is 48 Rm.

The price per volume of the Palaeontologisches Zentralblatt (Abt. B) is 48 Rm.; seven volumes have appeared.

Address: *Gebruder Borntraeger*, Berlin, W. 35., Germany

MAAS Determines Direction and Dip of Drill Holes

Drill Hole Compass

E. L. DERBY, Jr., Agent, Ishpeming, Michigan

14-7 CODE: McNeill's, 1908

LABORATORY FOR ROCK ANALYSES

Chemical analyses of rocks and rock minerals made with the accuracy required for research work in petrography: for students, geologists, and surveys. Moderate prices.

FRANK F. GROUT, in charge

GEOLOGY DEPARTMENT, UNIVERSITY OF MINNESOTA

MINNEAPOLIS, MINNESOTA

An A.A.P.G. Book (1939)

RECENT MARINE SEDIMENTS

A SYMPOSIUM OF 34 PAPERS BY 31 AUTHORS

EDITED BY

PARKER D. TRASK

U. S. GEOLOGICAL SURVEY, WASHINGTON, D. C.

PREPARED UNDER THE DIRECTION OF A SUBCOMMITTEE OF THE COMMITTEE ON SEDIMENTATION OF THE DIVISION OF GEOLOGY AND GEOGRAPHY OF THE NATIONAL RESEARCH COUNCIL, WASHINGTON, D. C.

This book is on the topic of Sedimentation and Environment of Deposition recently voted No. 1 in geological research of most importance to the progress of petroleum geology—in a poll of the 3,000 A.A.P.G. members and associates, conducted by the Research Committee. Throughout the book, the basic data—observational facts—are emphasized rather than speculative inferences.

- **736 pages; 139 figures**
- **Bibliographies of 1,000 titles; 72 pages of author, citation, and subject index**
- **Bound in blue cloth; gold stamped; paper jacket; 6 x 9 inches**

PRICE: $5.00, POSTPAID

($4.00 TO A.A.P.G. MEMBERS AND ASSOCIATE MEMBERS, LIBRARIES, AND COLLEGES)

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

BOX 979, TULSA, OKLAHOMA, U.S.A.

NEW BOOK LIST

The books in the following list are all recent publications. Address ECONOMIC GEOLOGY, Urbana, Ill. Books not in this list (except the publications of official Surveys and those of the Geological Society of America) will be furnished at Publishers' prices. THE PRICES OF ENGLISH BOOKS ARE QUOTED WITHOUT DUTY. THE PRICES OF ALL FOREIGN BOOKS VARY WITH THE EXCHANGE.

Ore Deposits of Magmatic Origin. By P. NIGGLI. Trans. by H. C. BOYDELL 2.70
Field Geology. 3d Ed. By F. H. LAHEE 5.00
German-English Geological Terminology. By W. R. JONES and A. CISSARZ. Pp. xv + 250. Cloth. 3.25
A French-English Vocabulary in Geology and Physical Geography. By G. M. DAVIES. Pp. ix + 140. Cloth, 8vo. 1.75
Treatise on Sedimentation. 2d Ed. Rewritten. By W. H. TWENHOFEL. Pp. xxvi + 914. Figs. 121. Cloth, 6 x 9 ..... 8.00
Metamorphism. By A. HARKER. Pp. ix + 260. Figs. 185. Cloth, 6 x 9 ..... 5.90
Mineral Deposits. 4th revised Ed. By W. LINDGREN 6.50
The Determination of the Feldspars in Thin Section. By K. CHUDOBA. Trans. by W. R. KENNEDY. Pp. 75. Figs. 50. Cloth, 8vo. 1.75
Die Bodenschätze des Staates Minas Geraes, Brasilien. By B. v. FREYBERG. Pp. xvi + 453. Figs. 73. Pl. 12. Paper 20.50
Grundzüge der Geologie und Lagerstättenkunde Chiles. By J. BRUGGEN. Pp. viii + 362. Figs. 69. Pl. 4. Paper 13.25
The Strategy of Raw Materials. By B. EMENY. Pp. 202. Maps, etc., 29 ..... 3.00
Handbook for Prospectors. 3d Ed. By M. W. VON BERNEWITZ. Pp. 372. Illus. 105. Cloth, 5 x 7¼ 3.00
Prospecting and Operating Small Gold Placers. 2nd Ed. By W. F. BOERICKE. Pp. 144. Illus. 30. Cloth, 5 x 7½ 1.50
The Geology of Southwestern Ecuador. By G. SHEPPARD. Pp. xi + 275. Illus. 195. Cloth 6.25
Gold Deposits of the World. By W. H. EMMONS. Pp. 552. Illus. Cloth, 6 x 9 ..... 6.00
Elements of Optical Mineralogy. Pt. I. Principles and Methods. 5th Ed. By A. N. WINCHELL. Pp. 263. Illus. 305. Cloth, 6 x 9 ..... 3.50
Ground Water. By C. F. TOLMAN. Pp. 576. Illus. Cloth, 6 x 9 ..... 6.00
Geological Nomenclature. Edited by L. RUTTEN. Pp. viii + 339. Illus. 58. Cloth, 8 x 11 ..... 6.75
The Cycle of Weathering. By B. B. POLYNOV. Trans. by A. MUIR. Pp. xii + 220. Cloth, 5½ x 8½ 2.75
Our Wandering Continents. By A. L. DU TOIT. Pp. 364. Illus. 48. Cloth, 8vo. 4.75
Principles of Structural Geology. 2d Ed. By C. M. NEVIN. Pp. 348. Figs. 163. Cloth, 6 x 9 .... 3.50
Economic Geology. 7th Ed. By H. RIES. Pp. 720. Figs. 378. Cloth, 6 x 9 ..... 5.00
Earth Lore. By S. J. SHAND. Pp. viii + 144. Figs. 33. Cloth, 5¼ x 7½ 1.75
The Science of Petroleum. By 300 authorities. 4 Vols. 85.00
Scientific Illustration. By J. L. RIDGWAY. Pp. 210. Illus. Cloth, 7 x 10 ..... 4.00
Introductory Economic Geology. 2d Ed. By W. A. TARR. Pp. 645. Illus. Cloth, 6 x 9 ..... 5.00
The Origin of Life. By A. I. OPARIN. Trans. by S. MORGULIS. Pp. 270. Cloth 2.75
Studies on the Periodicity of Earthquakes. By CHAS. DAVISON. Pp. ix + 108. Figs. 14. Cloth, 8¼ x 5½ 4.00
Minéralogie von Bolivien. By F. AHLFELD and J. M. REYES. Pp. viii + 89. Figs. 30. Paper, 10 x 6½ 4.25
Outlines of Geomorphology. By S. W. WOODRIDGE and R. S. MORGAN. Pp. xxi + 445. Figs. 272. Cloth, 6 x 9 ..... 4.50
Practical Oil Geology. 5th Ed. By D. HAGER. Pp. 455. Illus. Cloth, 6 x 9 ..... 4.00
Geology, Principles and Processes. 2nd Ed. By EMMONS, THIEL, STAUFFER and ALLISON. Pp. 447. Illus. Cloth, 6 x 9 ..... 3.75
A Descriptive Petrography of the Igneous Rocks. Vol. IV. The Feldspathoid Rocks, etc. By A. JOHANNSEN. Pp. 524. Cloth, 6⅝ x 9¾ 4.50
The Examination of Fragmental Rocks. Revised Ed. By F. G. TICKELL. Pp. x + 153. Figs. 54. Cloth, 10 x 7 ..... 4.00
Fundamentals of the Petroleum Industry. By D. HAGER. Pp. 435. Illus. Cloth, 6 x 9 ..... 3.50
This Earth of Ours. By V. T. ALLEN. Pp. 364. Illus. 250. Cloth, 5½ x 8¾ 3.50
Our Amazing Earth. By C. L. FENTON. Pp. 346. Illus. 126. Cloth, 6 x 9 ..... 4.50
Applied Geophysics. By A. S. EVE and D. A. KEYS. 3rd Ed. Pp. x + 315. Figs. & Pl. Cloth, 8vo. 4.25
Vanishing Lands. By R. O. WHYTE and G. V. JACKS. Pp. 321. Illus. Cloth, 6½ x 9½ 4.00
Geology and Allied Sciences. A thesaurus and coordination of terms. Pt. I. German-English. Pp. 400. Cloth, 5⅝ x 8⅛ 7.50
Geomorphology. By A. K. LOBECK. Pp. 720. Illus. Cloth, 6 x 9 ..... 4.50
Geology and Engineering. By ROBT. F. LEGGET. Pp. 642. Illus. Cloth, 6 x 9 ..... 4.50
Petroleum Production Engineering. Oil Field Exploitation. 2nd Ed. By L. C. UREN 10.00
Die Entstehung der Gesteine. By F. W. BARTH, C. W. CORRENS and P. ESKOLA. Pp. 400 ±. Illus. 200. Paper 3.50
Earthquakes and Other Earth Movements. 2nd Ed. By JOHN MILNE and A. W. LEE. Pp. 244. Illus. 83 ..... 4.10
Mine Examination and Valuation. 2nd Ed. By C. H. BAXTER and R. D. PARKS 5.00
Internal Constitution of the Earth. Edited by B. GUTENBERG. Pp. 413. Cloth, 6¾ x 9⅜ 9.00
Geology of China. By J. S. LEE. Pp. xvi + 528. Illus. 93. Cloth, 8vo. 7.00
Geology of South Africa. 2nd Ed. By ALEX L. DUTOIT. Pp. 556. Pl. 41. Figs. 68. Geol. Map. Cloth, 8vo. 5.00
Strategic Mineral Supplies. By G. A. ROUSCH. Pp. 473. Cloth, 6 x 9 ..... 4.25
Applied Geophysics. 3rd Ed. By A. S. EVE and D. A. KEYES 5.00
Recent Marine Sediments. Edited by P. D. TRASK. Pp. 736. Figs. 139. Cloth, 6 x 9 ..... 6.00
The Principles of Sedimentation. By W. H. TWENHOFEL. Pp. 593. Illus. Cloth, 6 x 9 ..... 3.50
Elements of Geology. 2nd Ed. By W. J. MILLER. Pp. viii + 524. Figs. 367. Cloth 3.75
Textbook of Geology. 2nd Ed. By LONGWELL, KNOPF and FLINT. Pp. ix + 540. Figs. 340. Cloth 4.00
Textbook of Geomorphology. By G. WORCESTER. Pp. 565. Illus. Cloth 6.00
Physiography of Eastern United States. By M. FENNEMAN. Pp. 691. Illus. Cloth 11.00
Die Bodenschätze Boliviens. By F. AHLFELD and J. M. REYES. Pp. vii + 199. Figs. 65. Map. Cloth, 6 x 9½ 9.50
Geologie der Deutschen Kolonien in Afrika. By E. KRENKEL. Pp. xii + 272. Pl. 6. Figs. 65. Cloth, 6 x 9½ 6.50
Geology of N. America. Vol. I. By R. RUEDEMANN and R. BALK. Pp. xi + 643. Pl. 14. Figs. 53. Cloth, 6 x 9½ 4.50
Descriptive Petrography of the Igneous Rocks. Vol. I, Revised. By A. JOHANNSEN. Pp. xxiv + 318. Figs. 145. Cloth, 6⅝ x 9¾ 5.00
Gebirgsbildung und Vulkanismus. By H. BECKER. Pp. viii + 220. Figs. 129. Cloth, 6½ x 9½ .. 12.00
The Throne of the Gods. By A. HEIM and A. GANSSER. Pp. 233. Pl. 220. Figs. 16. Map 5.00
Mineral Industry. Vol. 47, 1938. By G. A. RAUSCH. Pp. 783. Cloth, 6 x 9 ..... 12.00
Principles of Economic Geology. 2nd Ed. By W. H. EMMONS. Pp. 518. Illus. 650. Cloth, 6 x 9. 4.00
Structural and Field Geology. By JAS. GEIKIE. 5th Ed. Revised by R. CAMPBELL and R. M. CRAIG. Pp. 395. Pl. 69. Figs. 147. Cloth, 6 x 9 ..... 6.50

, Ill.
erica)
THE

2.70
5.00
3.25

1.75

8.00
5.90
6.50

1.75

20.50

13.25
3.00
3.00

1.50
6.25
6.00

3.50
6.00
6.75
2.75
4.75
3.50
5.00
1.75
85.00
4.00
5.00
2.75

4.00

4.25

4.50
4.00

3.75

4.50

4.00
3.50
3.50
4.50
4.25
4.00

7.50
4.50
4.50

10.00

3.50
4.10
5.00
9.00

7.00
5.00
4.25
5.00
6.00
3.50
3.75
4.00
6.00

11.00

9.50

6.50

4.50

5.00
12.00
4.00

6.50